7th INTERNATIONAL WORKSHOP ON LASER PHYSICS

(LPHYS'98)

Berlin, Germany

July 6-10, 1998

PROGRAM

AND

BOOK OF ABSTRACTS

Vol. 1

- **Modern Trends in Laser Physics**
- **Laser Spectroscopy**
- **Laser Cooling and Atom Optics**
- **Physics of Solid State Lasers**
- **Laser Methods in Medicine**

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7th INTERNATIONAL WORKSHOP ON LASER PHYSICS (LPHYS'98)

ORGANIZED BY:

General Physics Institute, Russian Academy of Sciences
International Journal „Laser Physics"
Max-Born-Institute for Nonlinear Optics and Short Pulse Spectroscopy, Berlin

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MEMBERS: **W. Becker, T. Elsässer, P. V. Nickles, H. Rottke, H. Weber**

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13. ABSTRACT (Maximum 200 words)

The Final Proceedings for 7th International Workshop on Laser Physics - LPHYS '98, 6 July 1998 - 10 July 1998

This is an interdisciplinary conference. Topics include strong-field phenomena, laser spectroscopy, laser cooling and atom optics, physics of solid state lasers, and modern trends in laser physics, including far IR, X-ray, and gamma ray lasers.

14. SUBJECT TERMS

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The DR. WILHELM HEINRICH HERAEUS UND ELSE HERAEUS-STIFTUNG was constituted for the furtherance of basic research in natural science, especially in the field of physics and in related fields. A traditional activity of the foundation is the support and organization of seminars.

Aim and Purpose of the 207. WE-Heraeus-Seminar:

The topic of the seminar is the interaction of atoms and small molecules with strong laser fields. As considered in the seminar a field is "strong" if within an order of magnitude it is comparable with the binding Coulomb field. The interaction is then beyond the reach of perturbation theory which has largely shaped physical intuition. Hence, various initially "counterintuitive" phenomena have emerged when the laser field approached this regime. Some touch on questions of very fundamental interest such as stabilization against ionization or time-dependent tunneling, others may turn out to provide completely novel experimental tools of wide interest, such as the generation of pulses of light of subfemtosecond duration or the shaping and control of electronic wave packets in atoms or molecules, to name just a few examples.

The seminar intends to provide a forum for the assessment of the status quo and for the identification of directions of future research.

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Topics and Scientific Seminars

The workshop consists of the following seminars (organized by the respective cochairs)

Modern Trends in Laser Physics
(including far IR, X-ray and gamma lasers)

P. Leiderer (Germany)
J. P. Manassah (USA)
K. A. Prokhorov (Russia)

Laser Spectroscopy

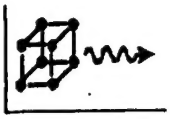
S. R. Hartmann (USA)
H. Walther (Germany)
V. M. Yermachenko (Russia)

Laser Cooling and Atom Optics

J. Baudon (France)
W. P. Schleich (Germany)
V. P. Yakovlev (Russia)

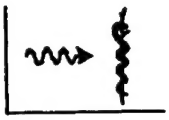
Physics of Solid State Lasers

G. Huber (Germany)
S. Nakai (Japan)
I. A. Shcherbakov (Russia)



Laser Methods in Medicine

S. A. Gonchukov (Russia)
G. Müller (Germany)
R. Steiner (Germany)



207. WE-Heraeus Seminar on "Strong-Field Phenomena"

W. Becker (Germany)
J. H. Eberly (USA)
M. V. Fedorov (Russia)

(*) These times are approximate and may vary from day to day and from seminar to seminar; please, check the detailed program

Rooms:
D1: Radisson hotel, Dom 1; D2: Radisson hotel, Dom 2; R3: Radisson hotel, 3rd room
M: Magnus House, 5 minutes' walk from the Radisson, cp. map

Plenary sessions take place in rooms D1 and D2 merged into one

Conference Schedule

	Monday	Tuesday	Wednesday	Thursday	Friday
9:00-10:30	Opening addresses	D. Pritchard	P.B. Corkum	W. Demtröder	E. Vinogradov
	P.L. Knight	E. Wintner	W.H. Lowdermilk	M. Raizen	B.H.T. Chai
10:30 - 11:00(*)	COFFEE				
11:00 - 12:45(*)	Room: D1 Room: M Room: D2	Room: D2 Room: D1 Room: R3 Room: M	F. DeMartini A. Stratonnikov	Room: D2 Room: D1 Room: R3 Room: M	Room: D1 Room: D2 Room: R3
12:45 - 14:00(*)	LUNCH				
14:00 - 16:15(*)	Room: D1 Room: M Room: D2	Room: D2 Room: D1 Room: R3 Posters 14:00 - 17:30 Room: Lobby	Room: D2 Room: M Room: D1	Room: D2 Room: D1 Room: R3 Room: M	Room: D1 Room: D2 Room: R3
16:15 - 16:45(*)	COFFEE				
16:45 - 18:50(*)	16.45: Departure by bus: Tour of "WISTA Science and Technology Park" Opportunity to visit laser and photonics institutes 19.30: Welcome party (WISTA Photonics Center)	Room: D2 Room: D1 Room: R3 17.30 -20:00 Room: R3	16.45: Departure by bus: Boat trip on Lake Wannsee and the Havel river to Schloss Glienicke Reception and conference dinner at Schloss Glienicke	Room: D2 Room: D1 Room: R3 Room: M	

207. WE-Heraeus Seminar "Strong-Field Phenomena"

Monday, July 6

Chair: J. H. Eberly (Rochester, USA)

11.00-11.35	D. D. Meyerhofer (Rochester, USA) "Strong field tunneling in atoms and the vacuum"
11.35-12.00	N. B. Narozhny (Moscow, Russia) "Simple QED processes in a strong two-color laser field"
12.00-12.25	J. W. Braun, J. C. Csesznegi, B. A. Smetanko, G. H. Rutherford, Q. Su, **R. Grobe** (Normal, USA) "Numerical solutions to the time-dependent Dirac equation"
12.25-12.50	C. H. Keitel (Freiburg, Germany) "Recollions and harmonics in relativistic laser-atom interactions"
12.50-14.00	lunch

Chair: A. Maquet (Paris, France)

14.00-14.35	P. H. Bucksbaum, M. P. Hertlein, E. R. Peterson (Ann Arbor, USA) "New resonant effects in ATI spectra: rescattering and electron-electron correlation"
14.35-15.00	H.-J. Kull, L. Dimou, J. L. Sanz (Aachen, Germany) "Hydrogen atoms in strong laser fields: quantum-mechanical and classical calculations of ionization and scattering"
15.00-15.25	D. Bauer, P. Mulser (Darmstadt, Germany) "Ultrafast ionization: TDSE calculations in intense laser pulse-solid interaction"
15.25-15.50	A. Cionga, G. Zloh (Bucharest, Romania) "Target dressing effects in electron-hydrogen scattering in bichromatic fields"
15.50-16.15	A. Jaron, J. Z. Kaminski (Warsaw, Poland) "Kroll- Watson low-frequency approximation revisited"

Tuesday, July 7

Chair: B. Wellegehausen (Hanover, Germany)

11.00-11.35	R. Sauerbrey (Jena, Germany) "Dense plasma generated by high-intensity lasers"
11.35-12.00	A. Pukhov, J. Meyer-ter-Vehn (Garching, Germany) "Relativistic laser plasma interaction by multi-dimensional particle-in-cell simulations"
12.00-12.25	P.-V. Nickles, M. P. Kalashnikov, P. J. Warwick, K. A. Janulewicz, W. Sandner, U. Jahnke, D. Hilscher (Berlin, Germany), M. Schnürer (Vienna, Austria), R. Nolte (Braunschweig, Germany), A. Rousse (Palaiseau, France) "Energetic particle generation in a hot dense plasma"
12.25-12.50	M. D. Feit, **A. M. Rubenchik**, B. W. Shore (Livermore, USA) "Interaction of ultra-short laser pulses with transparent dielectrics"
12.50-14.00	lunch

14.00-17.30: Poster Session

V. I. Arefyev, V. S. Beliaev (Moscow Region, Russia) "Mechanisms of atomic and nuclear processes stimulation in strong field of laser produced plasma"

A. Becker, F. H. M. Faisal (Bielefeld, Germany) "Interplay of electron correlation and intense field dynamics in double ionization of atoms"

S. Bivona, R. Burlon, C. Leone (Palermo, Italy) "Two-color photodetachment in the presence of an intense low-frequency radiation field"

I. I. Bondar, V. V. Suran (Uzhgorod, Ukraine) "Resonant structure of doubly-charged ions creation at nonlinear ionization of Sr and Ba atoms in infrared spectral range"

I. I. Bondar, V. V. Suran, M. I. Dudich (Uzhgorod, Ukraine) "AC-Stark effect at multiphoton ionization of Sr and Ba atoms in strong field of infrared laser radiation"

M. I. Dudich, V. V. Suran, I. I. Bondar (Uzhgorod, Ukraine) "Doubly-charged strontium ions formation under multiphoton ionization in 15000-16900 cm(-1)"

A. Egbert, D. Simanovskii, B. N. Chichkov, B. Wellegehausen (Hanover, Germany) "Time -resolved investigations on optically field ionized plasma"

C. Figueira de Morisson Faria, M. Dörr, W. Becker, W. Sandner (Berlin, Germany) "Time-frequency analysis of two-color high-harmonic generation"

C. Figueira de Morisson Faria, A. Fring, R. Schrader (Berlin, Germany) "Momentum transfer, displacement, and stabilization"

C. Guidotti (Pisa, Italy), H. Haken (Stuttgart, Germany), N. Rahman (Trieste, Italy) "Mapping, inverted harmonic oscillator, and harmonic oscillator with imaginary mass in high-order harmonic generation"

Ph. Hering, C. Cornaggia (Saclay, France) "Production of multicharged atomic ions from laser-induced multiple ionization of small molecules"

Ph. V. Ignatovich, V. T. Platonenko, V. V. Strelkov (Moscow, Russia) "High-order harmonic generation by a bichromatic field"

M. P. Kalachnikov, P.-V. Nickles, D. Rohloff, G. Kommol, W. Sandner (Berlin, Germany) "Solid-state chirped-pulse-amplification lasers for 10^19 W/cm^2"

G. L. Kamta, B. Piraux (Louvain-la-Neuve, Belgium) "Two-electron atoms in strong ultrashort laser pulses: correlation effects"

R. V. Karapetyan (Moscow, Russia) "Optical tunneling and finite motion of an electron"

A. E. Kazakov (Moscow, Russia) "Influence of strong ionizing electromagnetic field on decay of the pair of autoionizing atomic states"

R. Kopold, W. Becker (Berlin, Germany), M. Kleber (Munich, Germany) "Model calculations of high-harmonic generation in H2+"

R. V. Kulyagin, V. D. Taranukhin (Moscow, Russia) "Coulomb modification of relativistic spatial distribution of tunnel photoelectrons in superstrong laser field"

S. Magnier (Metz, France), M. Persico (Pisa, Italy), N. Rahman (Trieste, Italy) "Above-threshold dissociation and wave packet propagation"

A. I. Magunov, I. Rotter, S. I. Strakhova (Moscow, Russia, and Dresden, Germany) "Strong laser field effects in spectral lines of autoionizing atomic states"

N. L. Manakov (Voronezh, Russia), A. Maquet (Paris, France), S. I. Marmo, A. A. Krylovetsky (Moscow, Russia) "Closed form for amplitudes of two-photon transitions between H-like states with arbitrary quantum numbers"

E. Mese, R. M. Potvliege (Durham, England, and Diyarbakir, Turkey) "Multiphoton detachment and harmonic generation in the presence of a static electric field"

D. B. Milosevic (Sarajevo, Bosnia, and Nebraska, USA), F. Ehlotzky (Innsbruck, Austria) "X-ray atom scattering in the presence of a laser field"

R. Parzynski (Poznan, Poland) "Raman mixing of Rydberg angular momenta in multiphoton ionization probed by photoelectron angular distributions"

V. T. Platonenko, V. V. Strelkov (Moscow, Russia) "Generation of a single attosecond soft x-ray pulse"

R. M. Potvliege (Durham, England) "A program for time-independent calculations of multiphoton processes in one-electron atomic systems"

I. P. Prokopovich (Minsk, Belarus), J. Peatross (Provo, USA) "Direct shaping and amplifying of high-intense single attosecond pulses from high-intense femtosecond optical pulses in inert gases"

N. Rahman (Trieste, Italy), A. Rizzo (Pisa, Italy) "The (linear and) non-linear susceptibilities of acetylene relevant for high-order harmonic generation"

A. B. Savel'ev, S. A. Gavrilov, V. M. Gordienko, P. M. Mikheev, A. A. Shashkov, R. V. Volkov (Moscow, Russia) "Efficient hard x-ray production from femtosecond plasma induced in volume-structured solids"

A. Scrinzi (Vienna, Austria), B. Piraux (Louvain-la-Neuve, Belgium) "Two-electron atoms in short intense laser pulses"

M. B. Smirnov, V. P. Krainov (Moscow, Russia) "Hot electrons in the tunneling ionization of atoms"

G. Sommerer, M. Dörr (Berlin, Germany, and Brussels, Belgium) "Harmonic generation and propagation: double driving laser pulse"

G. Sommerer, H. Rottke, W. Sandner (Berlin, Germany) "Enhanced effiency in high-order harmonic generationusing sub-50 fs laser pulses"

M. E. Sukharev (Moscow, Russia) "Classical and quantum theory of orientation and dissociation of diatomic molecules and their ions in a strong laser field"

V. V. Suran, I. I. Bondar (Uzhgorod, Russia) "Proof of realization of two-electron mechanism of Ba2+ ions formation at multiphoton ionization of atoms in 9390-9460 cm(-1) spectral region"

V. V. Suran, I. I. Bondar (Uzhgorod, Russia) "Formation of Ca2+ ions at multiphoton ionization of atoms by radiation of linear and circular polarization in 15000-18700 cm(-1) spectral range"

C. Szymanovski (Freiburg, Germany), V. Véniard, R. Taïeb (Paris, France), C. H. Keitel (Freiburg, Germany), A. Maquet (Paris, France) "Effects of relativity in Dirac-model-atoms exposed to strong laser pulses"

V. D. Taranukhin (Moscow, Russia) "High-order harmonic generation in a dense medium"

S. Varró (Budapest, Hungary), F. Ehlotzky (Innsbruck, Austria) "Redistribution of electron energies at the interface between laser radiation filled space and vacuum"

E. A. Volkova (Moscow, Russia) "Advantages of direct numerical solution of non-stationary Schroedinger equation in the investigation of quantum system dynamics in strong laser field"

N. S. Zakharov, V. V. Rudenko (Moscow Region, Russia) "Magnetic fields of laser plasma formed at high-power radiation of a target by a HF laser"

D. F. Zaretsky, E. A. Nersesov (Moscow, Russia) "The coherent effects in the process of high-harmonic generation"

Chair: D. F. Zaretsky (Moscow, Russia)

17.30-17.55	P. Kálmán (Budapest, Hungary) "Nuclear decay by electronic transition in the presence of ionic surroundings and a laser field"
17.55-18.20	H. R. Reiss, A. Shabaev, H. Wang (Washington, USA) "Alteration of nuclear beta decay"
18.20-18.45	J. Bergou (New York, USA), P. Kálmán (Budapest, Hungary) "Lasing without inversion in the x-ray regime: hyperfine splitting and stability questions"
18.45-19.10	I. Averbukh, M. Shapiro (Rehovot, Israel), C. Leichtle, W. Schleich (Ulm, Germany) "Wavefunction holography"
19.10-19.35	B. Chichkov, S. Meyer, H. Eichmann, A. Egbert, B. Wellegehausen (Hanover, Germany) "Multiphoton parametric processes in an intense laser field"
19.35-20.00	A. Gontier (Saclay, France) "Atom-atom correlations induced by intense radiation"

Wednesday, July 8

Chair: P. H. Bucksbaum (Ann Arbor, USA)

13.45-14.10	J. H. Eberly, W.-C. Liu (Rochester, USA), R. Grobe (Normal, USA) "Two-electron correlation effects in 1-D model atoms"
14.10-14.35	K. T. Taylor, J. S. Parker, D. Dundas, E. Smyth, S. Vivirito (Belfast, UK) "Laser-driven helium"
14.35-15.00	M. Petersilka, **E. K. U. Gross** (Würzburg, Germany) "Towards a time-dependent density-functional description of multiphoton ionization of helium in strong laser fields"
15.00-15.25	F. H. M. Faisal, A. Becker, J. Muth (Bielefeld, Germany) "Intense-field many-body S-matrix theory: applications to processes in strong laser fields"
15.25-15.50	A. M. Popov (Moscow, Russia) "Dynamics of a two-electron quantum system in a strong laser field"
15.50-16.15	U. Eichmann, H. Maeda, W. Sandner (Berlin, Germany) "Collective multi-electron tunneling in strong fields: a working formula"

Thursday, July 9

Chair: P. B. Corkum (Ottawa, Canada)

11.00-11.25	Ph. Hering, **C. Cornaggia** (Saclay, France) "Laser-induced non-sequential double and multiple ionization of small molecules"
11.25-11.50	M. Brewczyk (Bialystok, Poland), K. Rzazewski (Warsaw, Poland), C. W. Clark (Gaithersburg, USA) "Two-dimensional Thomas-Fermi model of multielectron dissociative ionization of diatomic molecules"
11.50-12.25	R. R. Jones (Charlottesville, USA) "Manipulating electronic wavefunctions"
12.25-12.50	V. Véniard, R. Taïeb, **A. Maquet** (Paris, France) "Theory of two-color pump-probe determination of multiphoton ionization dynamics"
12.50-14.00	lunch

Chair: P. Agostini (Saclay, France)

14.00-14.25	H. G. Muller (Amsterdam, Netherlands) "Solving the time-dependent Schrödinger equation in two and three dimensions"
14.25-14.50	V. P. Krainov (Moscow, Russia) "New aspects of ionization of atoms and diatomic molecules by strong low-frequency laser fields"
14.50-15.15	G. G. Paulus, F. Zacher, H. Walther (Garching, Germany), W. Becker (Berlin, Germany) "Quantum tunneling interferences in strong-field ionization"
15.15-15.40	S. P. Goreslavskii, S. V. Popruzhenko (Moscow, Russia) "Strong-field limit in scattering of Volkov wave packets"
15.40-16.05	D. B. Milosevic (Sarajevo, Bosnia, and Lincoln, USA), **F. Ehlotzky** (Innsbruck, Austria) "Coulomb and rescattering effects in above-threshold ionization"
16.05-16.30	M. Yu. Kuchiev (Sydney, Australia) "Single-electron and many-electron processes in atoms in strong laser fields"
16.30-17.00	coffee

Chair: V. P. Krainov (Moscow, Russia)

17.00-17.35	D. Normand, S. Dobosz, J. P. Rozet, M. Schmidt, D. Vernhet (Saclay, France) "Clusters in strong laser fields"
17.35-18.00	A. D. Bandrauk, S. Chelkowski, C. Foisy (Sherbrooke, Canada) "Electron-nuclear dynamics of dissociative ionization in ultrashort intense laser pulses - Numerical simulations for H2+ with a parallel supercomputer"
18.00-18.25	J. H. Posthumus, J. Plumridge, M. K. Thomas, K. Codling, L. J. Frasinski (Reading, UK), A. J. Langley, P. F. Taday (Didcot, UK) "Laser-induced alignment of molecules on a vibrational timescale"
18.25-18.50	H. Rottke, C. Trump, W. Sandner (Berlin, Germany) "H2+ photodissociation and Coulomb explosion; a high-resolution study of these processes"
18.50-19.15	P. Dietrich (Berlin, Germany) "Dissociation of small molecular ions in strong infrared laser fields"

Friday, July 10

Chair: C. M. Bowden (Redstone Arsenal. USA)

11.00-11.25	K. Rzazewski (Warsaw, Poland), L. Plaja, L. Roso (Salamanca, Spain), M. Lewenstein (Saclay, France) "Attosecond pulse trains from a solid surface"
11.25-11.50	P. Agostini (Saclay, France) "Temporal dependence of high-order harmonics in the presence of strong ionization"
11.50-12.15	B. Piraux, A. de Bohan, Ph. Antoine (Louvain-la-Neuve, Belgium), D. B. Milosevic (Sarajevo, Bosnia) "Phase-dependent harmonic emission with ultrashort laser pulses"
12.15-12.40	L. Roso, L. Plaja, E. Conejero Jarque (Salamanca, Spain) "Relativistic effects in a plasma driven by a laser field"
12.40-13.05	Ph. Martin, S. Vivirito, G. Petite (Saclay, France) "Interaction of a strong laser field and a metal"
13.05-14.20	lunch

Chair: H. G. Muller (Amsterdam, The Netherlands)

14.20-14.45	S. Haan (Grand Rapids, USA) "Analytic and numerical investigations of near-threshold photodetachment of simple atomic systems in strong fields"
14.45-15.10	C. M. Bowden, S. D. Pethel (Redstone Arsenal, USA), C. C. Sung (Huntsville, USA), A. T. Rosenberger (Stillwater, USA) "Quantum-classical correspondence for intense-field ionization suppression in a short-range potential"
15.10-15.35	O. V. Tikhonova (Moscow, Russia) "Stabilization of an atomic system in a strong laser field and the Kramers-Henneberger approach"
15.35-16.00	N. Kylstra (London, UK) "Relativistic effects in laser-atom interactions at ultra-high intensities"
16.00-16.35	M. V. Fedorov (Moscow, Russia) "Analytical models and exact numerical calculations in the theory of interference stabilization of Rydberg atoms"

ORAL PRESENTATIONS

Temporal dependence of high-order harmonics in the presence of strong ionization

P. Agostini
CEA Saclay

The temporal behavior of the 19th harmonic of a Ti:sapphire laser generated in argon was investigated by a cross-correlation technique at intensities close to saturation. Pulses about twice shorter than predicted on the basis of the scaling law of the atomic dipole strength on intensity were found. Analysis shows that this is a consequence of both the intensity-dependent dipole phase and the depletion of the medium by ionization.

WAVEFUNCTION HOLOGRAPHY

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The problem of how to measure the wavefunction of a quantum system in amplitude *and* phase has attracted a lot of attention over the last few years. Such a reconstruction has been achieved for only a few systems, such as a single mode of the electromagnetic field [1,2], vibratory states of molecules [3], a single ion stored in a Paul trap [4], and an atomic beam [5]. In this paper we address the problem of measuring the quantum vibrational state of a molecule, and propose the concept of *Wavefunction Holography*.
In analogy to the ordinary optical holography, we interfere the *object* wavefunction to be measured with a known *reference* wavefunction. For this purpose, we employ a sequence of two time-delayed laser pulses which subsequently excite the object and the reference wavepacket in the excited molecular potential. This is similar to the recently introduced technique of wavepacket cross-interferometry [9]. The total time- and frequency-integrated incoherent fluorescence of the excited molecule, which is recorded as the function of the delay time τ, serves as a hologram. We show that these data contain enough information to extract the full quantum state of the object wavepacket. Moreover, we demonstrate the feasibility of wavefunction holography by numerically simulating the reconstruction of vibrational wavepackets in the $A^1\Sigma_u^+$ potential of sodium dimer. As the test examples we have used (i) a squeezed vibrational wavepacket, and (ii) a vibrational Schrödinger Cat state optically excited by femtosecond laser pulses from the ground $X^1\Sigma_g^+$ electronic potential. The method demonstrates a high quality reconstruction, and, in contrast to the emission tomography technique [3], it is capable of determining highly non-classical wavepackets in arbitrary anharmonic molecular potentials.

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Electron-Nuclear Dynamics of Dissociative Ionization in Ultrashort Intense Laser Pulses-Numerical Simulations for H_2^+ with a Parallel Supercomputer

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The time-dependent Schrödinger equation, TDSE, for the one-dimensional H_2^+, with both electronic and nuclear degrees of freedom included exactly, has been solved numerically to study dissociative ionization in molecules.

A wave function splitting technique was used with projections onto Volkov states,which allows one to circumvent the problem of lost information on electron and nuclear flux in standard absorbing boundary methods[1]. This technique allows us to calculate molecular ATI photoelectron kinetic energy spectra in the presence of moving nuclei, as well as complete spectra of dissociating and coulomb exploding protons, beyond the Born-Oppenheimer approximation. The ATI spectra show considerable structure as a result of electron-nuclear interaction during the dissociative-ionization process. The peaks observed in the calculated Coulomb explosion spectra of protons agree well with recent theoretical and experimental work [2] related to the nonperturbative phenomenon of CREI, charge resonance enhanced ionization [3].

In particular we will show that dissociative ionization of molecular ions such as H_2^+ contains much new information about electron-nuclear dynamics. Thus from our full non-Born-Oppenheimer TDSE solutions of H_2^+ in ultrashort intense laser pulses (800 nm;I> 10^{14} W/cm^2), we have been able to calculate ATD, Coulomb explosion and acompanying ATI spectra. The calculated low energy ATD proton spectra agree with a dressed-state [4] interpretation of laser-induced avoided crossings between the first two electronic states at high intensities. The high energy proton spectra agree with theoretical predictions from Coulomb explosions of protons at the CREI critical internuclear distance R_c obtained from a static model of electron ionization which includes charge resonance effects. ATI electron kinetic energy spectra show high energy components up to 15 U_p related to inelastic scattering of ionizing electrons with Coulomb exploding protons at large distances.

The present wave splitting method, which removes absorbing bound-

aries and uses asymptotic matching, enables us to calculate the complete electron and proton spectra, and thus constitutes a complete non-Born-Oppenheimer treatment of molecular dissociative ionization in an intense laser pulse. We are currently using this exact numerical method to establish the necessary and optimal conditions for obtaining the initial nuclear wave functions in a Coulomb explosion. This should lead to a new diagnostic tool for time-resolved molecular structure determination, which we call LCEI, Laser Coulomb Explosion Imaging [5].

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Ultrafast ionization: TDSE calculations and applications in intense laser pulse-solid interaction

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TDSE calculations

Numerically determined ionization rates for the field ionization of atomic hydrogen in strong and short laser pulses are presented. The laser pulse intensity reaches the so-called "barrier suppression ionization" regime where field ionization occurs within a few half laser cycles. Comparison of our numerical results with analytical theories frequently used shows poor agreement. An empirical formula for the "barrier suppression ionization"-rate is presented. This rate reproduces very well the course of the numerically determined ground state populations for laser pulses with different length, shape, amplitude, and frequency.

Intense laser pulse-solid interaction

A thin and dense plasma layer is created when a sufficiently strong laser pulse impinges on a solid target. The nonlinearity introduced by the time-dependent electron density leads to the generation of harmonics. The pulse duration of the harmonic radiation is related to the risetime of the electron density and thus can be affected by the shape of the incident pulse and its peak field strength. Results are presented from numerical particle-in-cell-simulations of an intense laser pulse interacting with a thin foil target. An analytical model which shows how the harmonics are created is introduced. The proposed scheme might be a promising way towards the generation of attosecond pulses.

LWI in the X-ray regime: hyperfine splitting and stability questions

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SUMMARY

Hyperfine splitting (HS) has been known to play a crucial role in lasing action in the X-ray regime [1]. Many Ne-like ions, from Ti (Z=22) to Ag (Z=47) have been observed to lase on the $3p \rightarrow 3s$ transition. At low Z, ions with an even Z have lased while those with an odd Z have not. At higher Z's, line ratios have been found to be very different for even and odd Z's. Hyperfine splitting can affect the gain of the laser line by effectively increasing the linewidth. Since the gain is inversely proportional to the linewidth HS will tend to decrease the gain. Experimentally, it has been found [2] that the gain coefficient can be reduced by as much as 40%. Using typical length configuration data for the active material this translates into an exponential gain factor of up to 50 – 100 smaller for odd Z nuclei, accounting for the lack of lasing in these materials.

It turns out, however, that, besides its adversary effect on usual laser gain, HS can be used advantageously in lasing without inversion (LWI, [3]) schemes. In this paper, we report of such a possibility. In one particular scheme of LWI nearly degenerate lower levels are needed to achieve inversionless lasing [4]. Hyperfine splitting in the X-ray regime falls in the domain of IR or optical frequencies. Therefore, it is possible to use optical lasers to create atomic coherence, with the appropriate phase relationship, between degenerate lower levels and, hence, cancel absorption.

First, we shall investigate the absorption coefficient for X-rays on transitions involving split lower levels and show that in a very narrow range of frequencies the absorption coefficient can become negative. Then, building on this result, we develop a full nonlinear theory of X-ray lasing without inversion. In particular, we relate the steady state intensity to atomic parameters, study the time scales involved in transient buildup and quantum features of the generated field. As it turns out, the field is less noisy than in ordinary X-ray lasers because, due to the lack of inversion, spontaneous emission plays a negligible role. In a two-mode version of the theory [5] we discuss stability of LWI operation. Finally, we also discuss the effect of Doppler broadening on the suggested scheme.

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Quantum-Classical Correspondence for Intense-Field Ionization Suppression in a Short-Range Potential

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Abstract

A one dimensional Gaussian potential is used to compare the intense field ionization rate calculated using a classical ensemble with recent results reported in the literature obtained using the adiabatic quantum high-frequency Floquet theory. The comparison of the results is better than qualitative, including the feature of non-monotonic decrease of ionization rate. Quantum-classical correspondence, in this case, is interpreted in terms of interference as the mechanism underlying ionization suppression.

Summary

A short range one dimensional potential with one bound state, and constant field was used recently [1] to compare the high-field ionization rates calculated by the high-frequency Floquet theory (HFFT) with those computed using an exact Floquet solution of the time-dependent Schrodinger equation. Quantum calculations using this potential have been reported previously [2], [3], and the potential holds some interest as somewhat representative of a negative ion, although the model is incapable of accounting for electron correlations, which may be quite important for intense fields. Our interest is concerned with the ionization rate calculation and quantum-classical correspondence in a simple model for a short range potential subject to an intense field, rather than calculational comparison between the HFFT and exact Floquet methods, or the particular details of a negative ion representation.

Two essential features of the calculation are that for sufficiently large fields, the ionization rate decreases with increasing field strength, and that the decrease is not monotonic, but oscillatory. We have demonstrated recently [4] that the same results can be obtained using a classical ensemble with adiabatic turn-on, and that these results are semiquantitative. It was shown that the results are entirely consistent with previous predictions [5] which showed that the classical-quantum equivalence for a long-range potential derived from the significance of interference and coherent superposition's of many quantum bound states within a denumerably infinite hierarchy. A comparison of ionization rates, and resultant ionization probabilities, for related short-and long range potentials, is given in Ref. [6]. It was shown [4] that under identical pulse conditions that the ionization rate has a significantly broader temporally integrated distribution for the Gaussian potential than for the Coulomb potential.

Our discussion here will focus upon the quantum-classical correspondence and analysis of the equivalence of the results from the classical model with results from the corresponding quantum approach for the short range potential. The oscillatory behavior of the ionization rate with increasing field strength, in particular, is an especially interesting facet for discussion. Our analysis indicates that, for the short range potential considered here, agreement with the quantum results suggests that the field-induced superposition of Kramers-Henneberger eigenstates, is not dominated by nonclassical interferences in which the Wigner quasiprobability distribution takes on negative values[7]. Our analysis suggests that quantum-classical correspondences indicate interference as the mechanism underlying ionization suppression, even in the adiabatic limit.

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Numerical solutions to the time-dependent Dirac equation*

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We review how split-operator FFT techniques can be applied to calculate numerical solutions to the time-dependent Dirac equation on a space-time lattice grid. These wave functions can be used to study the relativistic interaction of electrons with a nucleus and various external fields. We will revisit two examples of relativistic phenomena that occur on the spatial scale of the Compton wave length. These include Schrödinger's Zitterbewegung in position and spin and the time and spatially resolved dynamics of an electron as it scatters off a supercritical repulsive potential (Klein paradox) [1]. Both of these phenomena are quite paradoxical in nature and associated with the quantum localization problem. For length scales larger than the Bohr radius we will demonstrate how quantum wave packets evolve in homogeneous [2] and inhomogeneous magnetic fields [3,4] and also in very intense static electric fields [5,6]. Finally, we present our first results on the influence of strong static magnetic fields on the time-dependence of the ionization process [2].

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TWO-DIMENSIONAL THOMAS-FERMI MODEL OF MULTIELECTRON DISSOCIATIVE IONIZATION OF DIATOMIC MOLECULES

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Abstract

We have developed a two-dimensional time-dependent Thomas-Fermi model of diatomic molecule exposed to an intense femtosecond laser pulse. This model generalizes our earlier study of short pulse dissociative ionization of diatomic molecules [1] and cluster explosion [2]. We solve simultaneously two-dimensional hydrodynamic equations that govern the electronic charge distribution and the classical equations of motion for the nuclei and find dissociation accompanied by multielectron ionization (MEDI). Our calculations for a Cl_2 molecule interacting

with a linearly polarized laser pulse confirm the results obtained previously by using a one-dimensional model [1]. We find that the kinetic-energy defect, defined as a reduction of the ions final energy in comparison with the simple Coulomb explosion picture, is caused by the electronic charge remaining in the space between ions that screens the Coulomb interaction between the dissociating atomic ions. The model reproduces the main features of the experimental data [3] but it does not support the idea of stabilization nor enhanced ionization due to electron localization introduced previously.

We have also done calculations for Cl_2 exposed to an intense circularly polarized laser pulse. We find that the maximum ion kinetic energies attained during the molecular explosion are not as large as those found for linear polarization. However, since the screening effect is less strong in this case (although not negligible on the longer time scales) the final kinetic energies of the ions turn out to be very close. For higher laser intensities the screening effect becomes even more pronounced. More electrons are captured in the region between nuclei, perhaps due to some kind of stabilization of the system in the rotating potential.

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New resonant effects in ATI spectra: rescattering and electron-electron correlation.

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Simple semi-classical theories involving a single active electron have had great success in accounting for much of the structure observed in the lower-energy range of above-threshold ionization (ATI) spectra in rare gases, up to a photoelectron energy of about $2U_p$. ($U_p = e^2E^2/4m\omega$ is the classical averaged kinetic energy of the electron in the oscillating laser field, which is on the order of $2-5eV$ for most ATI experiments.) A closer examination of the ATI spectrum for argon ionized by intense $800nm$, $100fs$ laser pulses, reveals structure above $15eV$ that does not fit into these current models without adding modifications such as rescattering.[1–4]

We have examined this structure, and find several new phenomena that may help reveal new aspects of the high-intensity laser-atom interaction. First, we observe sharp resonances in the $15-25eV$ range. These peaks have sharp thresholds at laser intensities that seem closely correlated with the onset of Freeman resonances in the low-energy ATI spectrum. Unlike Freeman resonances, these new sharp peaks do not have the spectral pattern of Rydberg states. As the intensity is raised, the peaks do not appear in decreasing order of energy; furthermore, their spacing is greater than the spacing between Rydberg states.

We also examined the position of these resonances as the a function of the photon energy of the driving field. We found that the peaks shift by more than ten times the change in photon energy. This could mean that the high energy peaks are actually high-order excitations of resonances in the region of the ionization limit, more than ten photons away. Alternatively, this pattern of shifts could be due to resonant excitation by high harmonics of the driving field.

Another major finding is VUV fluorescent emission from atoms or ions at the same intensity where ATI occurs. We measured the time-history of this emission using time-correlated photon counting measurements; its lifetime resembles the excited 3d states in the neutral atom.

Finally, we have observed a heretofore unnoticed phenomenon in the low-energy ATI spectrum: a subtle intensity-dependent energy shift in the positions of the Rydberg resonances as the intensity is ramped through the threshold range for high-order electron resonances. The cause of this shift is not known for certain, but we have ruled out ponderomotive shifts or space-charge resonances.

One possibility is the excitation of a second electron from the outer shell of the ion to a Rydberg level. This scenario was recently explored in a paper by Bucksbaum et al.[4]. One of the problems with the excitation of a second electron from the core ion is that the energy required for such a process is more than the first electron can seemingly provide upon rescattering. However, an electron temporarily excited to a Rydberg state will move significantly in the laser field, and itself produce a time-varying field at the ion core

FIGURES

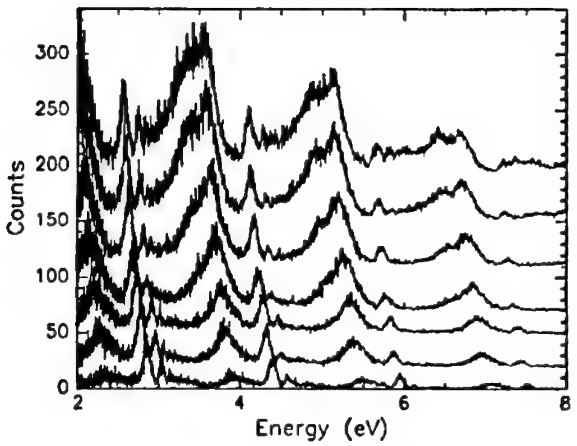

Fig. 1. ATI spectrum detail in argon for several intensities ranging from $5 \times 10^{13} W/cm^2$ (bottom) to $8 \times 10^{13} W/cm^2$ (top). This corresponds to the region between the $5f$ and $4f$ Freeman resonances. As the intensity is raised, the peaks shift to lower energy, in violation of the simple ponderomotive AC stark shift of a single weakly bound electron.

which could then resonantly excite such a transition during the course of several field cycles. Since this would be a resonant process over a longer time, the energy for the process is not required instantaneously from the electron. The sensitivity of such a resonance condition on intensity of the laser field could explain the sharp appearance onsets of the high order resonances, and would explain the correlation with the appearance of a low order resonance. One interesting aspect about this scenario is the fact that it predicts a wavelength dependent shift of the produced photoelectron peaks as the photon energy is varied, which goes with the harmonic of the light involved in the excitation.

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Target Dressing Effects in Electron-Hydrogen Scattering in Bichromatic Fields

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The role of the dressing of the target in the dynamics of laser-assisted electron-atom scattering was investigated in the last years for high scattering energies [1] and, more recently, for low scattering energies [2].

This work is focused on the investigation of target dressing effects in the domain of high scattering energies, for low and moderate field intensities. Special attention is paid here to the case of bichromatic fields. We choose to discuss here free-free transitions on the ground state of hydrogen atom in which *two different* photons are involved: two-photon absorption/emission and the case in which one photon is emitted and the other one is absorbed. In the regime mentioned before, perturbation theory might provide a sensible description of the process. Using the analytical form of the transition amplitude evaluated in the third order of perturbation theory, taken into account all the involved Feynman diagrams [3], we study angular distributions of high energy projectiles (50-500 eV) for weak fields. This analysis shows that the dressing of the target is important at small scattering angles ($\theta < 20^o$), similar to the monochromatic case [4].

The resonance structure of two-photon processes is investigated in detail for different polarizations of the photons. To illustrate our results, we present here the frequency dependence of the differential cross section of a high energy projectile (E_i=100 eV) for two-photon absorption. Both photons have linear polarizations and the initial momentum of the projectile is parallel to the polarization vectors. Two laser sources are considered, namely Nd:YAG (ω=1.17 eV) in Fig.(a) and KrF (ω=5 eV) in Fig.(b); the scattering angle is $\theta = 5^o$. Fig.(a) clearly shows that neglecting the atomic diagrams, in which both photons interact with the bound electron, would considerably alter the resonance structure between 9 and 12.5 eV. In Fig.(b) all the resonances are due to atomic diagrams: the contribution of the mixed diagrams, in which both electrons interact with the bichromatic filed, does not present any resonances. The modification of such structures for orthogonal linear polarizations and the effect of the helicity for circular polarizations will be presented at the conference.

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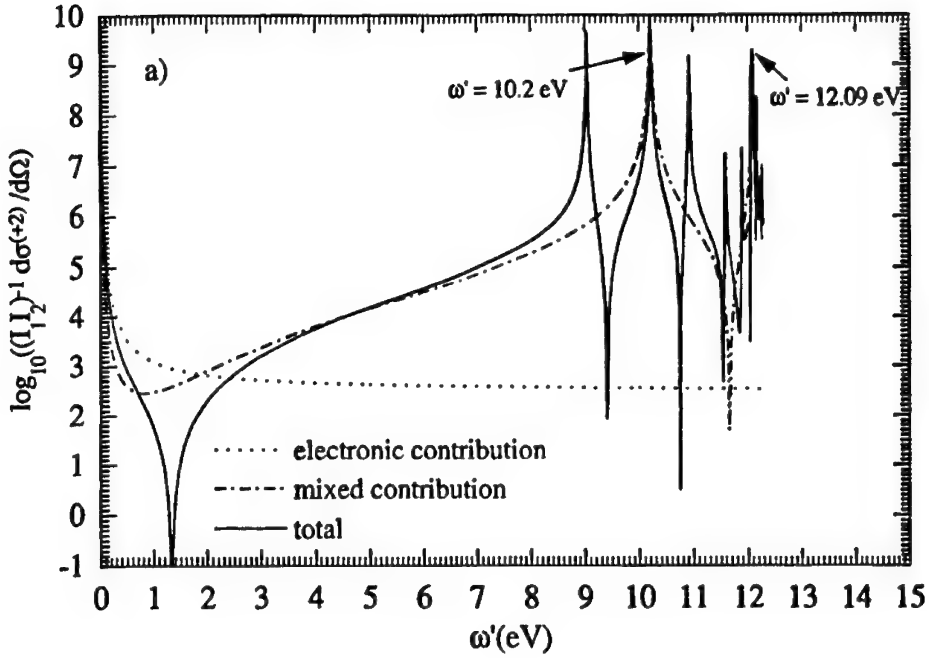
a)
ω' = 10.2 eV
ω' = 12.09 eV
electronic contribution
mixed contribution
total
log10((I1I2)-1 dσ(+2) /dΩ)
ω'(eV)

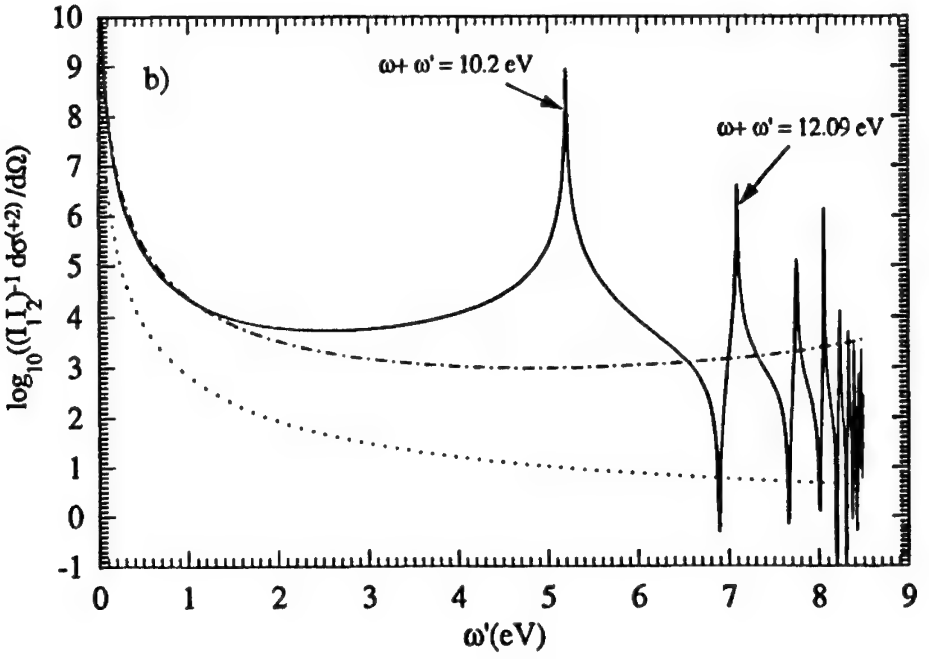
b)
ω+ ω' = 10.2 eV
ω+ ω' = 12.09 eV
log10((I1I2)-1 dσ(+2) /dΩ)
ω'(eV)

Figure 1:

Dissociation of small molecular ions in strong infrared laser fields

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Abstract

We study the multiphoton dissociation of H_2^+ in a strong mid-infrared field using a semiclassical, quasistatic approach. The dissociation is caused by the strong coupling of electronic states. We find a broad resonance far below the frequency of the first vibrational transition. This is caused by the field-induced dynamical distortions of the electronic ground state which shifts the classical oscillator frequency into resonance with the effective driving frequency.

Dissociation of small molecular ions, such as HCl^+ or H_2^+ in mid-infrared laser fields ($\lambda = 10\ \mu m$) has been observed experimentally at intensities of about 10^{14} Wcm^{-2} [1,2]. The mechanism of stepwise vibrational excitation cannot explain these findings because it would require much higher intensities due to the anharmonicity of the molecular vibration in the case of HCl^+ and fails completely for the case of H_2^+ which has no vibrational transition dipole moment. Instead, it was explained by barrier-suppression dissociation [1]. The coupling of electronic states in the strong field leads to the formation of a barrier on the electronic ground state. For sufficiently strong external fields the barrier is sufficiently suppressed so that the molecule can dissociate.

Here we extend the static model of barrier suppression to a time-dependent model of infrared strong-field dissociation of diatomic molecules. Using a semiclassical approach where the electron motion is treated quantum-mechanically and the nuclear motion classically on the quasistatic electronic potential curves we investigate the dynamics of the dissociation as a function of intensity, laser frequency and initial excitation of the molecule. In general, the dissociation yields show a strong nearly stepwise dependence on the intensity and the initial energy for a given frequency as predicted by the static barrier suppression model. However, the onset of dissociation shows a strong wavelength dependence (see Fig. 1 and Ref. 3) with a broad resonance at 800 cm^{-1} far below the first transition frequency at 2250 cm^{-1}.

There are two parts in the explanation of this subharmonic resonance. first, the effective driving frequency is twice the laser frequency because within the quasistatic approach the lower potential barrier is suppressed twice during an optical cycle.

Second, the distorted lower potential curve in the strong field will become broader with increasing field strength. This results in a lowering of the classical vibrational frequency due to the decrease of curvature in the minimum of the potential curve. Thus the classical frequency which is at 2250 cm^{-1} without external field will be lowered by the external field and shifted into resonance with the effective driving frequency.

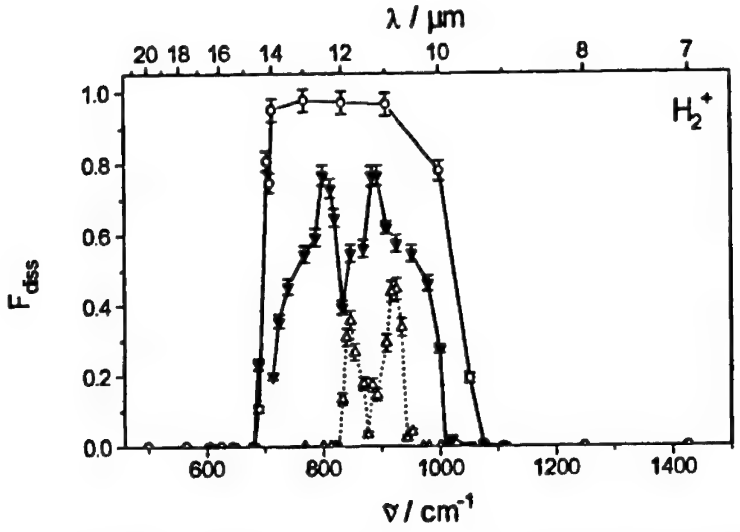

Fig. 1: Dissociation efficiency F_{diss} as a function of the frequency for infrared multi-photon dissociation of H_2^+. The molecular ion is initially in its ground vibrational state and exposed to a laser pulse with an envelope $E_0(t)=E_0^0 \sin^2 \pi t/\tau$. The peak intensity I_0 and pulse duration varied from $I_0=10^{14}$ Wcm^{-2}, $\tau=1$ ps (---o---), $I_0=10^{14}$ Wcm^{-2}, $\tau=250$ fs (---▼---) to $I_0=7.5 \cdot 10^{13}$ Wcm^{-2}, $\tau=250$ fs (···Δ···). The data extend up to 2500 cm^{-1} (4 μm) with $F_{diss}=0$ for $\nu > 1100$ cm^{-1}. The error bars indicate the statistical error of the data points.

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Two-Electron Correlation Effects in 1-D Model Atoms

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Abstract

A novel double-zone algorithm is used to calculate time-dependent two-electron wave functions for one-dimensional fully correlated two-electron model atoms. The double-zone algorithm divides computational space into an "inner" zone (close to the nucleus) and an "outer" zone, and treats "inner" wave functions with an exact spectral method and "outer" wave functions with a decomposition into canonical basis states[1,2]. Using the double-zone technique, the number of spatial grid points can be increased by an order of magnitude compared to one-zone exact spectral calculations. With this advantage, we investigate the time-dependent behavior of two-electron ionization and observe a "knee" structure in the double-ionization signals. We will show "population jets" observed in the electron density plots for the regime in which the nonlinear characteristic of the ionization signals becomes apparent. We have exploited the flexibility of the numerical model to explore effects of two-electron correlation by empirically changing the value of the "correlation charge."

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Collective multi-electron tunneling in strong fields: A working formula

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It has been known for some time[1,2] that a) multiple ionization rates in strong laser fields are many orders of magnitude higher than predicted by simple analytical models and b) the main cause for this are electron correlations, leading to collective and simultaneous („non-sequential") multiple ionization processes. Elaborate and accurate ab-initio calculations have confirmed this assessment for some selected processes[3]. In this situation the need for simple, but powerful analytical models is ever increasing, if one requires to predict ionic charge state distributions after irradiation by strong fields. Typical applications for such models would be plasma related phenomena in strong fields, including incoherent x-ray generation and x-ray lasers, plasma dynamics, or fusion related processes. To our knowledge, no such models exist so far.

Here we present a surprisingly simple, semi-empirical generalization of analytical single-electron ionization theories, such as the „ADK-theory"[4], which describe ionization in the so called tunneling regime. Our model[5] is guided by the idea that multi-electron tunneling, if it exists, can only be non-sequential if the electrons move in a strictly collective fashion during the tunneling process. Any asymmetry in the electron motion, i.e. lagging of one electron, would immediately lead to recapture and, thus, to sequential processes. Also, tunneling in general depends most critically on the binding energy of the initial state. Non-sequential tunneling must therefore only depend on the *total sum of all binding energies* E_{total} of the active electrons. Modifying single-electron tunneling rate formulas to include the collective properties of N electrons we found the following result[5]: The rate $W_{collective}(N, E_{total})$ for collective N-electron tunneling in a strong laser field is apparently represented by the one-electron rate W_{ADK} in the ADK-theory, if the one-electron binding energy is replaced by the mean binding energy $E_{eff} = (E_{total} / N)$ of each of the active electrons

$$W_{collective}(N, E_{total}) \approx W_{ADK}(E_{eff})$$

Comparison with available experimental ion yield data for several atoms[1] and new results from our laboratory[2] gives satisfactory or even excellent agreement, within a factor of two to three, over at least five orders of magnitude below the saturation intensity (Fig.1). The improvement over existing analytical models (sequential ADK; dotted curve) is evident. There is a systematic deviation from experiment at low laser intensities, which is well known from single-electron tunneling and usually attributed to alternative processes like multiphoton ionization. The decisive 'knee' structure in multiply charged ion yield curves is, however, accurately reproduced, including its

wavelength dependence[5]. We stress that there is no adjustable parameter in the above formula, although comparison with un-normalized experiments requires one single overall normalization factor per atom. This approach, which will be further elaborated in our laboratory, allows for the first time the prediction of charge state distributions after strong field ionization by a simple and analytic formula.

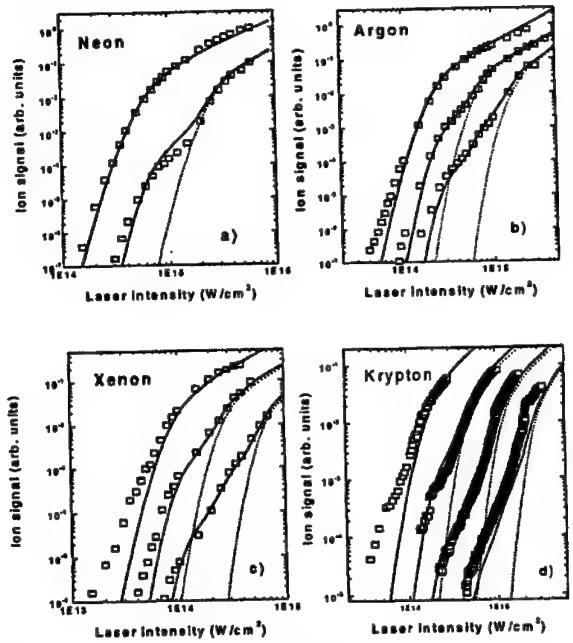

Figure 1): Comparison of theoretical results using our formula for collective tunneling (full curve) with experimental ion yield curves as a function of the laser intensity. a) Ne^{+} and Ne^{++} b), Ar^{+}, Ar^{++} and Ar^{3+} c) Xe^{+},Xe^{2+} and Xe^{3+}. Experimental data are from Larochelle et al [1]; d) Kr^{+}-Kr^{4+}, our experimental data[2]. The dotted line is the prediction of the one-electron ADK-theory.

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Intense-Field Many-Body S-Matrix Theory: Applications to Processes in Strong Laser Fields

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We have recently developed an S-matrix theory (the so-called intense-field many-body S-matrix theory (IMST)) [1,2] for analyzing processes occuring during the interaction of an intense laser field with many electron systems. In this paper we present the results of application of the theory to a number of problems of much current interest, namely, (i) generation of hot electrons in ATI [1-3], (ii) intensity dependence of laser induced double ionization of noble gas atoms [1-4], and (iii) 'enhanced-ionization' of simple and not-so-simple molecules [5].

The usual 'prior' or the 'post' form of the S-matrix series severely restricts the choice of the intermediate Green's function. In the new S-matrix expansion this is removed. The present formulation can, therefore, account for the dominant non-perturbative effects, already in the leading orders. The resulting series has been derived [1-3] by employing systematically three different partitionings of the total Hamiltonian, and can be written, using the unrestricted G^0, as:

$$(S-1)_{if} = -i\int_{-\infty}^{t} dt' < \Phi_f^0(t')|V_i(t')|\Phi_i^0(t') > - i\int_{-\infty}^{t} dt_1 < \Phi_f^0(t_1)|V_f(t_1)\int_{-\infty}^{t_1} dt' G^0(t_1,t')V_i(t')|\Phi_i^0(t') > - \dots \quad (1)$$

In the following illustrative figures we present some results of our recent calculations. Fig. 1 shows the 'hot electron'-spectrum for He at $\lambda = 780$ nm and $I = 1.2 \times 10^{15}$ W/cm^2, calculated both without (dotted curve) and including the rescattering diagram (solid curve), and compare them with the experimental data (dashed curve) [6]. The excellent agreement obtained here (up to more than 400 eV) unequivocally demonstrates the important role of the rescattering mechanism for their origin. In Fig. 2 we show the calculated intensity dependence of single and double ionization of Kr at $\lambda = 800$ nm and compare them with the experimental data [7]. This is the first time that such a remarkable agreement between the theory and the experiment has been obtained for Kr (and other noble gases, not shown here), including the well-known 'knee' structure, for the double ionization yields. Finally, in Fig. 3 we present the calculated ionization rates, at $\lambda = 532$ nm and $I = 8 \times 10^{13}$ W/cm^2, exibiting the so-called 'enhanced-ionization' process [8], for three different molecules

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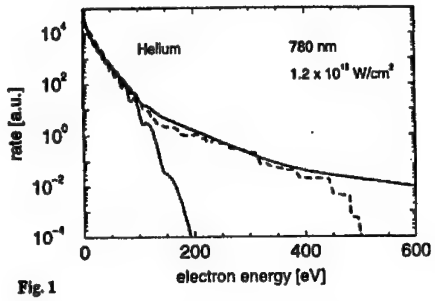

Fig. 1

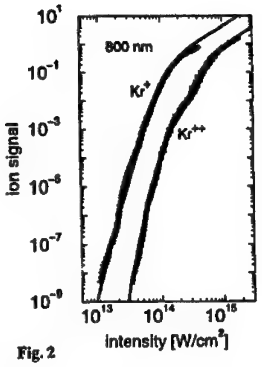

Fig. 2

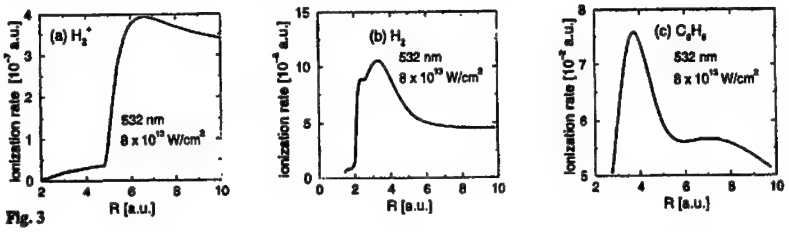

Fig. 3

(H_2^+ (panel a), H_2 (panel b), and C_6H_6 (panel c)), as a function of the nuclear coordinate, or the ring radius.

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ANALYTICAL MODELS AND EXACT NUMERICAL CALCULATIONS IN THE THEORY OF INTERFERENCE STABILIZATION OF RYDBERG ATOMS

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The main models and approaches used in the theory of strong-field interference stabilization of Rydberg atoms are discussed and compared with each other and with the results of exact 3D numerical calculations. The main results of the quasi-classical theory of strong-field photoionization and stabilization are shown to be in an excellent agreement with the results of exact numerical calculations.

Interference stabilization is known [1] to arise due to field-induced Raman Λ-type transitions between neighboring Rydberg levels of an atom. In a sufficiently strong light field, these transitions provide coherent re-population of Rydberg levels. Field-induced transitions from these to the continuum can interfere with each other, and this is a physical reason of interference stabilization of an atom. There are two main models or approaches to the theory of interference stabilization. The first of them is based on the adiabatic elimination of the continuum and solution of the arising equations for the time-dependent probability amplitudes to find an atom in the field-free Rydberg states [2-5]. The second approach is based on attempts to apply the quasi-classical approximation to solve directly the Schrödinger equation for an electron affected by both Coulomb and strong light fields [6-8]. Each of these two approaches is based on its own assumptions

and has its own limitations. In some sense, these two approaches are complementary to each other. The newest results obtained recently in the framework of each of these two approaches are described. Alternatively to these model solutions, the problem of strong-field photoionization from Rydberg levels is solved exactly, with the help of *ab-initio* numerical integration of the Schrödinger equation [9-11]. The main advantage of such an approach is its freedom of any approximations. On the other hand, technically, possibilities of such a solution are also limited. Nevertheless, wherever it's possible, the results of exact numerical calculations are compared with those of model solutions, and an excellent agreement with the quasi-classical theory is discovered. This coincidence is interpreted as a very serious confirmation of both the quasi-classical theory itself and the main ideas of interference stabilization and Λ-type transitions via the continuum.

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Interaction of ultra-short laser pulses with transparent dielectrics

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Material ablation with ultrashort laser pulses (USLP) is a promising technology. With USLP, very precise material removal can be accomplished with minimal collateral damage to surrounding material for both metals and dielectrics.

At high laser intensity, multiphoton ionization and subsequent electron avalanche processes produce sufficient electron density for strong light absorption in transparent material.

The theoretical description of the process will be presented. We calculate the ablation threshold, the spatial distribution of absorbed energy. The effect of enhanced light reflection by a plasma mirror formed on a dielectric will be described. Modeling of the subsequent plasma expansion and shock propagation in the material will be presented. Finally, we discuss some multipulse effects on laser modification of transparent dielectrics.

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Atom-atom correlations induced by intense radiation fields

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Abstract
The correlations arising between atoms strongly coupled with an intense radiation field are investigated within the framework of a fully quantized re-summed theory.We show that the correlations can be interpreted in terms of a sharing of the emission probability between the atoms involved. The principle of an experiment is presented.

Summary
The studies of correlations between quantum systems have stimulated a huge literature during the last decades. This field of investigation was open by Einstein Podolski and Rosen [1] who showed that all the predictions of quantum mechanics were not compatible with those of local realistic theories. This so-called E.P.R. paradox was illustrated by a *gedankenekseriment* involving two correlated spin ½ atoms coming from the decay of di-atomic molecules in singlet states. More recently the correlation of photons emitted in a cascade decay has been measured. Now, it is well established that neither theoretically (violation of Bell's inequalities [2]), nor experimentally (Aspect's experiments [3]), the non-locality of quantum mechanics can be contested. Actually, the problem consists of setting up an experiment whose results could only be interpreted in terms of non locality. In this respect, the recent progress of quantum *cryptography without eavesdropping* [4] is very promising. Up to now, the experimental schemes have concerned E.P.R. particles, i.e. particles having interacted in the past and delivered in such a way that they remain in their original states as long as no measurement is performed.
In the present work, we present an alternate way for studying quantum correlations. The fundamental difference between our model and the previous ones is that the quantum systems under consideration are continuously coupled with a third one. More precisely, we consider the correlations arising between two (or more) two-level atoms which do not interact with each others but are resonantly coupled with an intense radiation field [5]. These atoms are prepared in well-defined states and each of them is confined within areas where the radiation field has the same phase and the same polarization (reciprocal areas). It is assumed that the atom-field interaction does not perturb the radiation beam in order to prevent any information from being carried by the field.
The starting point of our theory is a fully quantum mechanical interpretation of cooperative emission, but in contrast to superradiant schemes, the atoms are coupled to an external field whose parameters can be controlled. We have made an all-order theory of the resonant one-photon emission by identical atoms which are coupled to the same radiation field. We have shown that the emission of a photon by anyone of the atoms is strongly influenced by the presence of the other atoms. This correlation arises whether the atoms lie within an interaction volume whose dimensions are small compared to the wavelength of the field or lie inside

remote reciprocal areas. In the last case, one could imagine that the correlation can be a way for transmitting informations, i.e. the ciphers of encoded messages.

The calculations make use of operator expressions obtained from exact summations of perturbation series displaying all-order contributions to the process we consider, i.e. the net emission of a single photon [6]. The computations are done in the case where the frequency of the laser field coincides with that of the 1S-2P transition in atomic hydrogen. The theory is extended to the case of three an four atoms in order to simulate the effects of on-phase and out-of-phase atoms on the correlation. It is found that on-phase atoms have a little effect on the correlation. Our investigations have been extended to the behavior of couples of correlated atoms. In the physical parts of the resonance curves, one verifies that the sum of probabilities to emit a photon by anyone of the two atoms is unity, as expected. Therefore the correlation between the atoms can be interpreted in terms of probability pumping. According to the Einstein's definition of realism, one can say that the reality of the photon emission is shared by all the atoms involved in the emission process.

Experimental scenarios are discussed to test the theoretical predictions. One of them, of them concerns photon emissions on both sides of a screen inserted in a laser beam. By collecting the emitted light at right angle, through narrow slits which can be precisely moved, one can model reciprocal areas.

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Strong field limit in scattering of Volkov wave packets

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Abstract

We compare the quantum mechanical description of the photoelectron scattering from the residual ion and the laser assisted electron scattering in plasmas [1] in the strong field limit. In this context the status of the cassical model of rescattering [2] is discussed. An approximate analytic formulae is presented for the energy spectrum within the ATI plateau.

The amplitude of rescattering is derived by solving the nonstationary Shrodinger equation for an atomic electron interacting with a laser field. The wave function is looked for as a sum of the initial bound state and a new unknown function $\phi(\vec{r},t)$. An inhomogeneous equation for the coefficients of a decomposition of $\phi(\vec{r},t)$ in the Volkov states denoted as $C(\vec{p},t)$ is solved by iterations in the atomic potential $V(\vec{q})$. In the zero oder $C_0(\vec{p},t)$ describes ionization in the Keldish approximation. The next iteration accounts for the interaction of the ionized wave packet with the parent ion and the transition amplitude is given by [3]

$$iC_1(\vec{p},t\to\infty)=\int\limits_{-\infty}^{+\infty}dt\int\frac{d^3\vec{q}}{(2\pi)^3}C_0(\vec{q},t)V(\vec{q}-\vec{p})exp\{i\int\limits_{t_*}^{t}d\tau(\epsilon_{\vec{p}}(\tau)-\epsilon_{\vec{q}}(\tau))\} \qquad (1)$$

where $\epsilon_{\vec{p}}(t)$ is the instant kinetic energy in the laser field of a classical electron with the drift momentum $\vec{p}$.

For the incident packet consisting of a single Volkov wave $C_0(\vec{q},t)=\delta(\vec{q}-\vec{k})$ Eq.(1) describes the laser assisted scattering [1]. In strong fields when the ponderomotive energy essentially exceeds the photon energy ($z=U/\omega\gg 1$) the transition amplitude could be calculated either by using the asymptotic expansions for the Bessel functions in [1] or by applying the stationary phase method to integrate over t in (1). The equation for these stationary points in the latter case

$$\epsilon_{\vec{p}}(t_s)=\epsilon_{\vec{k}}(t_s) \qquad (2)$$

is interpreted in quantum theory as the Landau-Zener crossing of time dependent energy levels [4]. The same condition (2) is adopted in the classical model of rescattering [2] where it is considered as the energy conservation for elastic scattering.

It worth mentioning that contrary to the classical appearance of that kinematical relation the corresponding probability calculated from (1) and the duration of the scattering process (i.e. time interval of an order of $\omega^{-1}z^{-1/2}$ around t_s) contain the Planck constant.

If electrons with small initial drift momentum $\vec{k} \to 0$ are scattered at an angle θ with respect to the direction of linear polarization their spectrum in the drift energy $\epsilon = p^2/2$ has sharp cutoff at $8U\cos^2\theta$. A nonzero value of the initial drift energy increases the cutoff energy and, for example, it reaches $\epsilon = 18U$ along $\theta = 0$ at $k = F/\omega$. The angular distribution of scattered electrons with a fixed energy ϵ consists of two wings confined to angles satisfying $\epsilon/8U \leq \cos^2\theta \leq 1$ with a sharp maximum at the lower boundary.

The basic distinction of the ionization from plasmas comes from the fact that the incident state is a coherent superposition of many Volkov waves. We use in (1) the coefficients $C_0(\vec{p}, t)$ calculated in the tunneling regime for lineary polarized field [3]. They properly reproduce the oscillations and spreading of the ionized wave packet in the coordinate space. The scattering amplitude (1) is reduced to a two-fold integral over two times and calculated by stationary phase method. One of the equations for the stationary points is given in Eq.(2) and the other says that at the time of scattering the electron returns to the ion position [2].

Advancements in calculations due to the stationary phase method being supplemented with some minor simplifying assumptions allow to derive an analytic expression for the energy spectrum within the ATI plateau. It accounts for the influence of the core of a complex multielectron ion on the shape of the spectrum by means of the ions's formfactor. The dependencies on the laser and atom parameters are explicity seen and reproduce features of the experementally obseved spectra [5]. These include the cutoff at ten ponderomotive potentials, a slight decline to higher energies and an overall decrease at high intensities. In addition the formulae predicts an overall enhancement of the plateau with increasing laser frequency.

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"Analytic and numerical investigations of near-threshold photodetachment of simple atomic systems in strong fields"

One-photon near-threshold photodetachment is examined theoretically using one-dimensional model systems. Earlier work has indicated the formation of a long-lived °bound dressed stateý that extends far from the atomic core. This talk will review basic ideas regarding the formation of the bound dressed state, its collapse at laser turnoff, and the kinetic energy spectrum of electrons emitted during laser turn on or during turn off. Interference between the two bursts of outgoing population are considered. Effects of ramping the laser on and off will be discussed.

LASER INDUCED NON-SEQUENTIAL DOUBLE- AND MULTIPLE-IONIZATION OF SMALL MOLECULES

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Non-sequential double ionization of neutral small molecules such as N_2, CO_2 or C_2H_2 is observed using a linear polarized 50 fs laser pulse at λ = 800 nm in the 10^{13}-10^{15} W/cm^2 laser intensity range. The corresponding charge separation channels, such as $N^+ + N^+$ or $O^+ + CO^+$ for respectively N_2 and CO_2, follow similar laser intensity dependences as the detected dications N_2^{2+} or CO_2^{2+}. In consequence the two-electron ejection process occurs at short internuclear distance following the Franck-Condon principle and the detected molecular dication and charge separation channels come from the same molecular complex resulting from the laser excitation. Non-sequential double ionization of molecular ions is also detected using the laser intensity dependences of the molecular decay channels involving 3 missing electrons such as $N^{2+} + N^+$ or $O^+ + C^+ + O^+$ for respectively N_2 and CO_2. The non-sequential electron dynamics will be discussed in comparison with existing models of molecules in strong laser fields.

Kroll–Watson low–frequency approximation revisited

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The free–free transitions have attracted a great deal of attention since, on the one hand, they permit the experimental observation of multiphoton processes at relatively moderate laser field intensities while, on the other hand, from theoretical point of view, they require nonperturbative techniques for treating the laser–matter interaction. Most of the experiments on laser–assisted scattering of electrons have been performed with the use of CO_2 laser and their results have been successfully analysed using the soft photon approximation known also as the Kroll and Watson theory [1]. This was true until recent experiments of Wallbank and Holmes [2], where comparison of experimental findings with predictions of the Kroll–Watson theory revealed enormous discrepancies for small scattering angles. Such a large discrepancy was completely unexpected and Wallbank and Holmes suggested that the electron–atom polarization potential and the laser field–induced dipole potential of target atoms might be responsible for the observed divergence.

In the context of the Wallbank–Holmes experiments we have investigated thoroughly the off–shell effects in the laser–assisted potential scattering [3]. It appears that these effects are the manifestation of the diffractive character of laser–assisted electron–atom scattering which is responsible for the observed discrepancy of the experimental results and the Kroll–Watson theory. The low–frequency approximation for non–resonant free–free transitions means that, apart from the factor $\exp(-iE_{p_i}t)$, the exact scattering wave function $\psi^{(+)}_{p_i}(r,t)$ of an electron interacting with both a static potential and a laser field is a slowly varying function of time and that the condition $\omega/E_{p_i} \ll 1$ is well fulfilled. Under such assumptions one can approximate the exact scattering wave function $\psi^{(+)}_{p_i}(r,t)$ by a modified Gordon–Volkov wave function, which has already been used in our earlier works [4] in the context of multiphoton ionization and high harmonic generation. The results of our work demonstrate that the low–frequency approximation does satisfactorily explain experimental results provided that a static electron–atom interaction is still significant at distances comparable or larger than the incident electron's de Broglie wavelength. A static polarization potential can be considered as an example of such interaction. Our calculations performed for a potential which modeled a static polarization potential came out to be in a good agreement with experimental results, i.e. obtained cross sections are by many orders of magnitude larger than those predicted by the Kroll–Watson theory.

Our numerical analysis suggests that the specific form of the static potential

is not crucial, as long as the range of interaction is sufficiently large. To get more insight into the physics of the considered problem we have studied thoroughfully the case when the potential of the target and projectile interaction is modeled by the square well potential. The advantages of using this potential are that most part of the calculations can be done analytically and it is possible to study the dependence of the differential cross sections on different parameters such as for example the width or the depth of the potential well.

As expected, for large scattering angles our theory and the Kroll-Watson formula give similar results. This is related to the fact that the Kroll-Watson formula can be reconstructed from our theory provided that an additional assumption is made, i. e., that an elastic off-shell scattering amplitude $f_{el}(\boldsymbol{p}, \boldsymbol{q})$ is a slowly varying function of its arguments $\boldsymbol{p}$ and $\boldsymbol{q}$. This condition is, however, violated not only for a resonant scattering, but also for a small-angle scattering by potentials with a range of interaction comparable to the incident electron's de Broglie wavelength. Henceforth, it shows that a non-Coulombic and relatively long-range character of electron–atom interaction is crucial for a proper analysis of small-angle free–free transitions in a low-frequency laser field.

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Manipulating Electronic Wavefunctions

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Abstract

Half-cycle electric field pulses have been used to combine positive ions and free electrons to produce bound electronic wavepackets in atoms.

Summary

Strong unipolar electric field pulses can be used to manipulate the electronic wavefunction in atoms. Specifically, recent experiments have demonstrated that subpicosecond "half-cycle" pulses can alter the momentum distribution of highly excited Rydberg eigenstates, producing electronic wavepackets with novel dynamic properties.[1,2] In the terms of classical physics, HCPs impart an impulsive momentum "kick" to a Rydberg electron, altering its evolution.

HCPs have also been used to probe wavepacket evolution in atoms. In the limit that the pulse duration is much less than any time scale for wavepacket evolution, the energy transferred to an electronic wavepacket during its interaction with a HCP depends only on the impulse delivered by the field and the electronic momentum distribution. Therefore, by measuring the probability for ionizing a wavepacket as a function of HCP field strength, the wavepacket's time-dependent momentum distribution can be monitored.[2-4]

Conversely, our most recent experiments have shown that HCPs can *extract* momentum from free electrons, facilitating their capture by positive ions. In the experiments, calcium atoms in the singlet 4s4p J = 1 level are photoionized into the 4sed continuum using a 1.5 psec, 390 nm laser pulse. The ejected electron leaves the atom in the form of a shell of probability amplitude. A sub-picosecond HCP, generated by gating a large aperture GaAs photoconductive switch with a 130 fsec 780 nm laser pulse, provides a unidirectional kick that halts the expansion of a fraction of the free electron wavepacket within a small solid angle on the escaping probability shell.

Currently, we detect the amount of bound state population that results from recombination. The efficiency of the process has been monitored as a function of the HCP field strength, polarization, and delay relative to the launch of the continuum wavepacket. These parameters determine the spatial extent and orientation of the bound wavepacket at the instant that it is created. In addition to producing novel wavepackets, HCP assisted recombination can be used to measure the angular distribution of near zero energy continuum wavepackets. We have also studied the recombination process in the presence of an additional static field, where angular and radial oscillations complicate the continuum electron dynamics and lead to complicated temporal structure in the recombination probability. In the future we anticipate using an additional HCP to directly probe the dynamics of these novel wavepackets.

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Nuclear decay by electronic transition in the presence of ionic surroundings and laser field

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Abstract

A new, general way for decay acceleration of nuclear isomers located in plasma surroundings and irradiated by appropriately tuned, moderately high power lasers is presented. It is stated that if Coulomb de-excitation of a nuclear isomeric state of a free ion is accompanied by ejection of an electron from the projectile ion then this process can be accelerated and can lead to an enhanced decay rate of the isomer if it is surrounded by slow heavy charged particles of high enough density. Ion number densities ($10^8 - 10^{14}\ cm^{-3}$) that are necessary for decay rate acceleration may be achieved in gas discharges and the atoms with nuclei beeing in the isomeric state may be effectively ionized by the method used in resonance ionization spectroscopy, which is capable of ionizing the addressed element with a high probability. Concerning the strong dependence of the discussed process from several nuclear and atomic characteristics it is followed up choosing Xe isomers as test isotopes.

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RECOLLISIONS AND HARMONICS IN RELATIVISTIC LASER-ATOM INTERACTION

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The experimental availability of lasers in the intensity regime around and above 10^{19} W/cm^2 has opened a new era of research for atom-laser interaction [1]. Since the ponderomotive energy of electrons driven by such radiation is no longer negligible as compared to the electron rest mass, conventional non-relativistic theoretical descriptions lose their validity and it is important to apply relativistic treatments. Those have involved initially free electron approaches [2], followed by classical [3] and quantum [4] relativistic theories for laser atom interaction and lately some attention was placed on theories describing radiative back action and pair creation in ultra intense fields.

Relativistic laser atom interaction so far however has not fulfilled its hope as a source of coherent high frequency radiation. The reason is obvious: the large momentum transfer of the incoming photons implies essentially instantaneous ionization, inhibiting any chance for a recollision of the electron wavepacket with its own nucleus. We discuss the extent of this ionization and means of imposing recollisions of the ionized electron with its own nucleus with additional appropriately designed electromagnetic fields [5]. Alternatively the dynamics and radiation of electrons is investigated which are injected into the interaction zone with the laser field with a velocity opposite to which it would gain on average in such a relativistic laser field.

We focus on the relativistic theory of atoms interacting with strong laser fields in the framework of the numerical investigation via three dimensional classical Monte Carlo simulations [3] and the two dimensional Dirac equation [4], which

will be reviewed in the beginning of the talk. Considerable attention will be put in understanding the various influences governing the dynamics of electron wavepackets in relativistic laser fields, which are in particular magnetic field and mass shift effects, the break down of the dipole approximation and to a smaller extent spin flips, pair creation and radiative back action of the emitted field. We show that ionization increases due to the magnetic field component of the laser field even in the high frequency regime and that this presents the main problem for high harmonic generation. It will be shown up to which regime of parameters the atom can still compensate for the momentum transfer of the incoming field in the propagation direction. In the regime where this may not be prevented means of enforcing recollisions will be discussed. Then emphasis will be placed on the radiation and radiative reaction of classical relativistically accelerated electrons without and with the possibility of one or several recollisions with its own or other nuclei.

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New Aspects of Ionization of Atoms and Diatomic Molecules by Strong Low-Frequency Laser Field

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Summary

This report contains review of recent theoretical developments in the problem of ionization of atoms, simple diatomic molecules and their ions by strong low-frequency laser radiation.

A compact analytical generalization of Landau-Dykhne approach is derived that includes rescattering of electrons in the tunneling ionization of atoms by low-frequency laser field. It is used for calculations of electron energy spectra in high-energy region [1]. Most of the essential features of recent measurements are reproduced analytically, that is, the onset, the extent and the relative height of the plateau. Coulomb correction is taken into account in the calculations. The angular spectrum of high-energy electrons is also derived analytically. It was shown that laser radiation with only small part of initial phases of the laser field can produce high-energy electrons.We obtained as well as simple analytical expressions describing quantum tunneling interferences both for low-energy part and for high-energy part of electron energy spectrum. Our analytical results are in agreement with the numerical calculations of Paulus et al [2].

Analytical expressions are obtained for energy and angular distributions of ejected electrons at the barrier-suppression ionization of complex atoms and atomic ions by low-frequency laser radiation [3]. The results reduce to previously known expressions in the case of tunneling results of the Ammosov - Delone - Krainov approach in the limit of weak fields compared with the barrier-suppression fields.

Simple analytical expressions are obtained for the energy and angular distributions of outgoing electrons in ionization of a molecular hydrogen ion by a strong low-frequency laser field as well as for the ionization rates [4]. The cases of linear and circular polarization of the laser radiation are studied.

It is shown that in contrast to the case of the ionization of atoms oscillations appear in the energy spectra of the photoelectrons as a function of their kinetic energy [5]. The well-known limits for the tunneling ionization rates for the hydrogen atom by a strong low-frequency laser field are obtained in the case of large internuclear separations.

A theory of classical rotation and alignment of diatomic molecules with and wihout permanent dipole moments and of their molecular ions in strong laser fields is considered [6]. Conditions under which molecular axes are aligned with the field, which is presumed to be linearly polarized, have been determined. The analysis leads to a conclusion that molecules exposed to ultrashort laser pulses continue to rotate even after the end of the laser pulse. The effect of dynamic chaos on the rotational angular velocity in strong laser field is discussed.

Vibration, rotation and dissociation of the simple diatomic molecular Cl_2^+−ions and H_2^+−ions perturbed by a strong laser pulse with the linear polarization are considered in the frames of classical mechanics. It is found that the duration of the laser pulse influences the rotation of the molecular axis and the vibration of the internuclear separation. The molecular axis of the heavy molecular Cl_2^+−ion is strongly rotated after the end of the ultrashort laser pulse, while the alignment of the H_2^+−ion axis occurs in the rise of the long laser pulse due to quick dissociation. Angular distributions of protons in dissociation of H_2^+−ion are calculated [7].

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Single-electron and many-electron processes in atoms in strong laser field

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A review of an idea of the "atomic antenna" which has been suggested in [1] and developed recently in [2,3] is given. Consider multiphoton many-electron processes when an atom is placed in a laser field. Suppose that first single-electron multiphoton ionization takes place. Then in the vicinity of the atom there appears the ionized electron which is bound by atomic forces no more, it can propagate freely, and therefore strongly interacts with the external field. This interaction results in the wiggling of the ionized electron which can make its kinetic energy be high in some moments of time. There is a possibility that the ionized electron returns to the parent atom and transfers the absorbed energy to it [1]. This can result in a number of phenomena including multiple ionization, ionization with excitation, high harmonic generation. The wiggling energy can also be transfered into excitation of high ATI levels. The described mechanism makes all these phenomena much more probable then the direct absorption. The first ionized electron for these processes plays a role similar to antenna in conventional radio devices.

It is important that the process of the single-electron ionization requires that the ionized electron goes under the potential barrier long way out from the atom. It emerges from under the barrier, roughly speaking when the potential of the external field becomes comparable with the atomic potential. This can happen in two points up and down the field. This picture of the single-electron process follows from the Keldysh approach [4], which a recent modification has made quantitatively reliable [5]. The firstly ionized electron appears from under the potential barrier at the points, starting from which the electron wave function propagates in all directions creating the complicates pattern in the angular distribution for the single-electron process [5]. This fact is very important for many-electron processes. The possibility for the firstly ionized electron to propagate in *any* direction from some points separated from the atom allows return of the ionized electron to the parent atomic particle. This fact ensures that the atomic antenna mechanism works for *any* field strength. In the strong field the wiggling energy can be high enough to put he mechanism in action by itself. For weaker fields the ATI states of the firstly ionized electron become important [2,3].

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Hydrogen atoms in strong laser fields: Quantum-mechanical and classical calculations of ionization and scattering

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In the past years, the interaction of intense laser pulses with atoms has attracted much attention in the context of above threshold ionization (ATI), optical harmonic generation (OHG), over-the-barrier ionization (OBI) and stabilization. To account for these phenomena, there has been growing effort to solve the underlying Schrödinger equation by time-dependent non-perturbative methods. In this work, the interaction of a hydrogen atom with a strong laser field is treated by both quantum-mechanical and classical non-perturbative methods. Results on ionization rates, energy spectra and angular distributions of photoelectrons are discussed.

The time-dependent Schrödinger equation (TDSE) is solved numerically by an alternating-direction implicit finite-difference method. Different types of boundary conditions are discussed to truncate the numerical solution at the boundaries of the numerical grid. In particular, exact radiative boundary conditions have been derived. These have been successfully applied to a one-dimensional model atom [1]. The general numerical method has been validated for the present purposes by comparison with exact solutions for a laser driven gaussian wavepacket in the absence of the atomic potential and for resonant excitations of Rabi-oscillations of the 1s-2p transition. In all cases considered, the numerical solution has been found in good agreement with theoretical predictions.

Ionization is studied as a function of the light frequency. Three characteristic regimes have been distinguished. At low frequencies, the ionization process is quasi-static and ionization rates then can be determined as a function of the instantaneous field strenght only. For this purpose a ramp field with a constant final field strength is used. The calculated ionization rates are compared with the quasiclassical tunneling theories of Landau and of Ammosov, Delone and Krainov. Dependencies of the quasi-static approximation on the rise time of the ramp are also discussed. At intermediate frequencies wave packets emitted during successive half-cycles of the light wave can partly interfere due to scattering. This phenomenon is demonstrated by characteristic interference patterns in the wave function of the outgoing electron.

Finally, at high frequencies multiple scattering indicates a transition to multiphoton ionization. Characteristic ionization waves, corresponding to this regime are presented.

The scattering regime is further studied by use of the Kroll-Watson theory for potential scattering in a laser field [2]. It is shown that this theory predicts a scattering plateau in the photoelectron energy spectrum with an energy cut-off at $8U_p$ (U_p: ponderomotive potential). Bessel function modulations of the energy spectrum in the polarization direction of the laser field, a typical feature of KFR-theories of multiphoton processes, can be simply explained by side lobes in the angular distribution at corresponding energies.

In addition to the quantum-mechanical calculations, a relativistic classical particle ensemble in phase-space has been considered [3]. This model applies to over-the-barrier ionization at high intensities, where an initially bound electron can be ionized on a classical trajectory. The predictions of this model on ionization rates and energy spectra are evaluated for different laser pulses. Dependencies on the pulse shape and on the intensity of the pulse are shown to be closely related to the instant of ionization of the electrons during the pulse. In the nonrelativistic regime, the energy spectrum is found in good agreement with previous theories and measured spectra. In the relativistic regime, however, the model indicates saturation of the photoelectron energies above several atomic units due to the complete ionization of the atom in the beginning of the laser pulse.

Further work is underway addressing the applicability of radiative boundary conditions for general 3-dimensional calculations and for studying mutual dependences between collisional and field ionization.

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RELATIVISTIC EFFECTS IN LASER-ATOM INTERACTIONS AT ULTRA-HIGH INTENSITIES

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Abstract

We discuss some of the recent progress that has been made in the theoretical study of laser-atom interactions at laser intensities which are sufficiently high so that relativistic effects must be accounted for. In particular, we consider the modification of the laser-atom dynamics in the stabilization regime, i.e. the high frequency regime where non-relativistic theories predict a decrease in the ionization of atoms with increasing laser intensity.

In recent years, much effort has been directed towards the theoretical investigation of laser-atom interactions at laser intensities which require the use of non-perturbative approaches. Nearly all of these studies have been performed in the dipole approximation using the non-relativistic quantum theory. However, when the laser intensity becomes sufficiently large, relativistic effects will become important. This is expected to occur when the ratio of the ponderomotive energy U_p (i.e. the cycle-averaged quiver energy) of the electron in the field to the electron's rest mass energy becomes comparable to unity. In atomic units, this ratio is $q = U_p/c^2 = \mathcal{E}_0^2/4\omega^2c^2$, where $\mathcal{E}_0$ is the peak strength of the electric field component, ω is the angular frequency of the laser light and c is the velocity of light.

When the frequency of the laser is low, a quasi-static ionization picture in which the electron moves in an instantaneous effective potential given by the Coulomb potential and the instantaneous electric field has proved useful. As the laser intensity increases, the ionization mechanism will pass from a quasi-static tunneling to quasi-static field ionization regime so that at very high intensities the investigation of laser-atom interactions essentially reduces to the study of free, laser driven (relativistic) electron wavepackets.

The situation is quite different for the case of a high-frequency laser due to the phenomenon of stabilization, i.e. the increasing lifetime of atoms with increasing laser intensity, in high frequency, high intensity laser fields. This effect was first studied within the Floquet framework and subsequently demonstrated in the direct numerical integration of the time-dependent Schrödinger equation (see for example the contributions in [1]). For sufficiently high intensities, a number of interrelated issues arise concerning the validity of a non-relativistic approach, and hence the degree of stabilization of atoms. These

include the modification of the electron's quiver motion by the magnetic field component and retardation effects, both of which are not present in the dipole approximation, relativistic effects which involve the dressing of the mass of the electron due to its relativistic motion in the laser field and spin effects.

Important initial studies directed towards gaining an understanding of these effects include the testing of the validity of the dipole approximation [2], relativistic, classical Monte Carlo simulations [3] and the formulation of a relativistic version of the high-frequency Floquet theory in the Kramers frame [4]. Ultimately, issues concerning the stabilization of atoms in ultra-intense laser pulses can be addressed by numerically solving the time-dependent Dirac equation. This is a formidable task since computationally the problem scales approximately as $\mathcal{E}_0^3/\omega^4$. For this reason, preliminary studies have considered the relativistic one-dimensional Schrödinger equation [5], the one-dimensional Dirac equation [6] and the two-dimensional Dirac equation [7]. In one dimension, magnetic field and retardation effects are not included and one can only be concerned with effects due to the relativistic quiver motion of the electron along the laser polarization direction. Kylstra *et al* [6] considered a maximum electric field strength of $\mathcal{E}_0 = 175$ a.u. and angular frequency of $\omega = 1$, giving $\eta = U_p/c^2 \simeq 0.4$, so that the ponderomotive energy is comparable to the electron rest mass energy. The one-dimensional studies indicate that the relativistic quiver motion tends to inhibit ionization and thus increase the stabilization of the atom. In two-dimensions, the range of phenomena is richer, allowing for the "figure eight" quiver motion of the electron, retardation and spin coupling dynamics. The calculations are, however, intensive. Rathe *et al* [7] made use of a Cray T3D having 256 processors and preliminary insights into the wavepacket and spin dynamics have been gained. The above mentioned numerical results and future directions will be discussed.

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Interaction of a strong laser field and a metal*

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The problem of the interaction between a laser field and a metallic surface is investigated theoretically. To stress the fundamental role of the collisions during the interaction with the laser field we will present some recent experimental data showing that in the infra-red (10 microns) the observed total photocurrent and the photoelectron spectrum can be explained only if one consider that collisions processes play a central role [1]. As we will show, in the infra-red region an electron around the Fermi level experiences in average one collision every half optical cycle. Going back to optical or near UV wavelengths, we will try to answer the following question, particularly crucial for coherent control in metals [2]: how many collisions are necessary to destroy definitively the coherence of the motion? For instance, the signature of this effect should be the vanishing of the harmonics (or at least the appearance of noise) of the fundamental laser frequency. To do that, we are developing a new model based on the one dimentional time dependent Schrödinger equation [3].

We start from a linear chain of atoms which mimics the periodic potential "seen" by a test electron in a quasi-free electron metal. This "crystal" potential is built as a series of screened coulombic potentials. Outside the

lattice, the potential is constant and adjusted in order to reproduce the work function of the metal under consideration. After diagonalization we obtain well known band structures with characteristic gaps at the end of each one-dimensional Brillouin zone. For eigenvalues below the vacuum level, the corresponding eigenstates extend in the whole crystal and can be seen as superpositions of Bloch functions taking in account the boundary conditions imposed by the presence of the square potential. Above the vacuum level, we find as expected that the electron has a larger probability to be outside the lattice. The laser is supposed to impinge on the chain at grazing incidence and the electric field is parallel to the chain. The amplitude of the electric field is, in the case of metallic reflection, space dependent: constant in vacuum and damped on a length taken equal to the skin depth inside the chain. In this framework, the notion of "surface" appears naturally because the laser irradiates only one side of the chain.

In this approach, the main difficulty is to include properly the transport of the electron in the lattice. We build a wave packet from the eigenstates of the periodic potential. Then, by including some defects in the chain, it is possible to provide it a resistivity. The defects consist in short range local modification of the lattice (impurities) and extended modifications of the potential due to the excitation of ionic vibrations (phonons) whose amplitude depend on the temperature. The density of impurities and the temperatures can be adjusted to modify the scattering rate of the electrons and, conseguently, the action of the collisions on the absorption processes (ionisation) and harmonics production.

We will present some comparison between this new developing approach which includes the transport of the electrons and a former model where the time-dependent Schrödinger equation was solved starting from one single "Bloch" state and then individual contributions from states around the Fermi level (namely all states between E_f and E_f minus the energy of the photon) were summed incoherently. In addition, we will show that a very simple classical calculation is enough to explain number of features in the infra-red region of the spectra.

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Strong Field Tunneling in Atoms and the Vacuum

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Abstract

It is well known that electrons can be tunnel-ionized from atoms or ions in intense laser fields. In field strengths near the QED critical field, electron-positron pairs can be tunnel ionized out of the vacuum. The physics is similar, with the primary difference, the value of the critical field strength.

This talk will present results of detailed comparisons of experimental results and theoretical predictions of the tunneling ionization of electrons from atoms and ions, and the tunneling of electron-positron pairs from the vacuum.

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Coulomb and Rescattering Effects in Above-Threshold Ionization

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Abstract: We present a generalization of the S-matrix theory of above-threshold ionization, which includes both the Coulomb and the rescattering effects. The Coulomb effects are responsible for a considerable increase of the ionization rates, while the rescattering effects give rise to the appearance of the second plateau of the ionization spectrum. Our results are in excellent agreement with the recent experiments. We show that the sidelobe positions correspond to the last rounded top before the cutoff of the ionization spectrum for the corresponding angle. Our model is simple and can be easily generalized to different inert gases.

Recent experiments [1] have shown new features of the photoelectron spectrum in the above-threshold ionization of inert gases. Presently, there is no quantum-mechanical theory which is able to explain these results satisfactorily. Furthermore, for such high intensities as used in these experiments ($\sim 10^{15}\,\mathrm{W/cm^2}$) it is presently impossible to treat the problem by direct integration of the time-dependent Schrödinger equation. On the other hand, using quasiclassical considerations one can predict some of the results of [1], but certainly not the quantum-mechanical interferences which are observed. Besides, there are quantum-mechanical models with short-range potentials [2], but neither of them takes into account that the true atomic potential is of long range. We show that the short-range features of the atomic potential become important when the ionized electron rescatters at the atomic core. We have developed a consistent S-matrix formalism which includes both, the long-range and short-range atomic interactions. The S-matrix expansion, which we obtained has the form $S_{fi} = S_{fi}^{(0)} + S_{fi}^{(1)} + \cdots$, namely

$$S_{fi} = -i \int_{-\infty}^{\infty} dt \langle \Phi_{f,x}^{(-)}(t) | \Big\{ H_L(t) | \Phi_{\mathrm{in}}(t) \rangle + \int_0^{\infty} d\tau V_s G_x(t, t-\tau) H_L(t-\tau) | \Phi_{\mathrm{in}}(t-\tau) \rangle + \cdots \Big\},$$

where Φ_{in} is the initial state which is a solution of the Schrödinger equation with the atomic binding potential V, without the interaction with the laser field H_L. The final state $\Phi_{f,x}^{(-)}$ propagates under the influence of the Hamiltonian $H_x = \mathbf{p}^2/2 + H_L + V_c$ where V_c is the Coulomb potential. The Green's operator G_x corresponds to the Hamiltonian H_x and V_s is the short-range part of the atomic core potential. The physical interpretation of this result is the following. Due to the interaction with the laser field H_L, the electron is ionized from the in-state. After that, the electron propagates in the laser field in which it also feels the long-range Coulomb potential. It can then leave these fields to be observed experimentally. This corresponds to the first term $S_{fi}^{(0)}$ of the above expansion and was considered in [3]. It can, however, happen that during its propagation the ionized electron comes back to the atomic core and scatters at the short-range part of the ionic potential. After rescattering, the electron propagates out of the fields and can be observed. This is described by the second term $S_{fi}^{(1)}$. In order to obtain a simple result which can be managed without large computer facilities we made the following approximations: (i) The exact final electron state is approximated by the improved Coulomb-Volkov wave ansatz. This approximation was successfully used in [3]; (ii) The intermediate Green's operator G_x in $S_{fi}^{(1)}$ is replaced by the Volkov Green's operator. This is the usual approximation made in the case of

strong laser fields (so called strong-field approximation); (iii) The integral over momenta, which appears in the first-order S-matrix element $S_{fi}^{(1)}$, is replaced, using the saddle point method, by a series in which as the expansion parameter quantity $\hbar/\tau$ is used, where $\hbar$ is Planck's constant devided by 2π and τ is the return time. We only retain the zeroth-order term, which corresponds to a version of the time-dependent WKB approximation and can be justified by the fact that for the higher energies of rescattering (into which the experiments [1] gave new insight) the return time is large. All matrix elements which appear in the result obtained in this way can be expressed in analytic form, so that the computation of the ionization rates can be easily done.

We will first present our results for the direct ionization rates. In the case of hydrogen atoms we calculated the total ionization rate as a function of the kinetic energy of electrons ionized by a monochromatic or by a bichromatic laser field. We compare the results obtained using the length and the velocity gauge. In the case of the bichromatic laser field the phase-dependent effects are clearly visible. Our main results are the differential ionization rates obtained, taking into account both, the Coulomb and the rescattering effects. We calculated these rates for a hydrogen atom and for a Yukawa-type short-range potential. Our numerical results show that the Coulomb effects are responsible for a considerable increase of the ionization rates, while the rescattering effects give rise to the appearance of the second plateau of the above-threshold ionization spectrum. Coulomb effects change the behaviour of the rates at the first plateau, but they do not influence the qualitative behaviour of the spectrum of the high-energy electrons in the second plateau. Our results are in excellent agreement with recent experiments [1]. Our theory predicts the correct position of the cutoff of the energy spectra for different angles between the ionized electron momentum and the polarization vector of the laser field. The evaluated sidelobes are also at the right observed positions and we show that these positions correspond to the last rounded top before the cutoff of the above-threshold ionization spectra for the corresponding emission angle. It should be stressed that the advantage of our theory is that it can be easily applied to more complicated systems than is the hydrogen atom, such as inert gases.

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Solving the time-dependent Schroedinger equation in two and three dimensions

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Progress in computer technology has made it possible to tackle problems with a PC that would have defied the worlds most powerful supercomputers of a decade ago. Nevertheless, the efficiency of the algorithms used has a strong impact on the magnitude of the problems that can be handled succesfully. This is not only true with respect to programming efficiency or sophistication of the numerical analysis; the physical description of the problem (e.g. choice of coordinates, proper exploitation of gauge freedom) can be just as important. As solving the time-dependent Schroedinger equation is concerned, photo-ionization is one of the harder problems: Typical ionization yields are small (often less than 0.1% per cycle), requiring large accuracy to recognize it against the background of the initial-state wave function. Optical frequencies are slow on the timescale of atomic evolution, requiring many timesteps. Photoionization generates rapidly moving photo-electrons near the origin, that travel through the entire grid to large distances, requiring large radial grids with high spatial resolution.

This presentation discusses the various problems one encounters in the integration of the time-dependent Schroedinger equation, and how they have been overcome in the development of a computer code that can easily handle two or three-dimensional problems, with fourth-order convergence in both spatial and temporal grid spacing. In addition some results will be shown on high-order ATI of argon with linear, and (hopefully) elliptically polarized light.

SIMPLE QED PROCESSES IN A STRONG TWO-COLOUR LASER FIELD

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Abstract

The method for the calculation of the probabilities of QED effects arising in the interaction of high energy photons and electrons with super intense two-colour laser pulses is developed. The probabilities of photon emission by an electron and e^-e^+ pair production by a photon is obtained. It is demonstrated that the probabilities of the processes essentially depend on the intensity distribution between field components.

In this report we consider the processes of photon emission by an electron and e^-e^+ pair production by a high energy photon colliding with two-colour laser pulse of high intensity. The nonlinear quantum-electrodynamic effects have been under intensive experimental study since powerful table-top lasers were made recently. The experiment on study of QED at critical field strength [1] is underway at SLAC now.

The plane bichromatic wave model is employed for description of two-colour laser pulse which is assumed to be prepared by a frequency tripling crystal placed on the way of a strong laser beam of linear polarization. Behind the crystal the field consists of two linearly polarized components with frequencies ω and 3ω. The results obtaned for an arbitrary phase shift between field components.

We derived spectral distribution and total probability rate of the processes for different polarization planes of the field components. The results are differ essentially for the cases when the field components are polarized in the same plane and in mutually perpendicular planes. In both cases the probabilities of both processes essentially depend on the intensity distribution between field components.

The contribution of the third harmonic to the total probability rate of pair production depends nonmonotonically on the intensity distribution between field components in the case of the field components polarized in the same plane. In the case of perpendicular polarizations the corresponding probability exceeds those in the monochromatic field of the same intensity at any intensity distribution between field components.

The contribution of the first two harmonics to the total probability of photon emission decreases as one increases the intensity of the field component with frequency 3ω. On the contrary the contribution of the third harmonic increases.

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Energetic particle generation in a hot, dense plasma

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Highly intense ultrashort Ti:Sa-laser pulses focussed onto solid targets produce a very hot and dense plasma. This plasma-solid interaction is characterized by the appearance of energetic electrons, ions and hard x-ray photons. The energetic distribution of these particles depends strongly on the irradiation conditions and their investigation is highly important to get a better understanding of the complex physical processes responsible for particle generation and in order to develop scaling rules for the energy transfer from the laser pulse. Results about hard x-ray emission in the intensity range higher than $3*10^{18}$ W/cm^2 are reported using calibrated thermoluminescence dosemeters. For the measurement of the spectral energy fluence in the energy range from 15 keV to 700 keV a 9-channel spectrometer was used. .

The scaling of the x-ray signals was studied by varying the incident laser energy within one order of magnitude and the pulsewidth within two orders of magnitude. From the x-ray dose the conversion rate of the laser energy into hot electrons has been estimated indirectly. The dependence of the hard x-ray emission on target thickness was studied to derive conclusions about the importance of hot-electron transport inhibition. At intensities of about 10^{19} W/cm^2 the energy distribution of hot electrons in the range between 20 keV and 1 MeV has been directly measured for the first time by a 10 m long time- of -flight- electron spectrometer. A hot electron temperature of 210 keV was deduced.

Explosion of clusters in intense laser fields: ionic fragments and X ray generation

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When submitting big rare gas clusters to strong laser intensities, they absorb an important amount of energy and then explode into fast, multi-charged atomic fragments. To measure the charge state and the start-up energy of these fragments, we use a modified time of flight mass-spectrometer in which an additional magnetic field is applied. The ion trajectories towards the detector are bent by the magnetic field as a function of the ion charge and speed. For Xenon clusters, we have found evidence for 30-fold charged fragments presenting start-up energies up to 1MeV.

The knowledge of the fragments energy and charge allows to reconstitute the interaction in the very beginning and to describe the following stages of the cluster explosion. First of all, the laser field removes one or more electrons from each atom within the cluster. Immediately after ionization these electrons are "cold" and stay within the cluster, but after a few optical cycles they are heated through numerous collisions with the ions in presence of the laser field: numerous of electrons escapes the cluster which induces a positive charge on the cluster. The cluster explodes because of the electrostatic repulsion between surface ions and the center part expands according to a hydrodynamic expansion of the so-called "nanoplasma" into the vacuum.

The relative weight of each of these two explosion mechanisms depends on the efficiency of the collisional heating , increasing with Z^2, but also on the cluster size. Thus, for intermediate size clusters, consisting of up to a few hundreds of thousand atoms with low Z, we observe that the Coulomb explosion is the prevailing mechanism: this is the case of Argon. For bigger clusters consisting of high Z atoms such as Xenon, the hydrodynamic expansion is dominant. However, the fastest ions observed always result from Coulomb ejection from the cluster surface.

Recent experiments have demonstrated the presence of strong X-ray emission arising from radiative recombination of inner shell vacancies of multiply

charged ions which are initially created by electron impact excitation and ionization within the hot nanoplasma. In particular, we observe L-shell emission in the case of Krypton and Xenon clusters and K-shell emission for Argon. Our results concern the measurement of the absolute X-ray photon yield in the keV range. We find that the flux is independent from the polarization of the laser field and increases with the power 3/2 of the laser peak intensity. Moreover, the flux increases as the square of the mean number of atoms in each cluster [Dobosz et al. 1997]. The mean charge state observed for ions lying within the clusters and emitting such X-rays has been determined to 15^+ in the case of Argon, for example.

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Quantum Tunneling Interferences in Strong Field Ionization

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The ionization of atoms in intense laser fields displays some typical phenomena. One of these is above-threshold ionization (ATI), i. e. the absorption of more photons than necessary for ionization, leading to a series of peaks in the electron energy spectra. It is remarkable that the main features are qualitatively similar for different atomic systems, in particular for the rare gases. A lot of insight was gained from a classical model that treats the atom as a source providing electrons via tunneling. Subsequently, the atomic binding potential is ignored and the electrons are described by classical trajectories merely in the laser field.

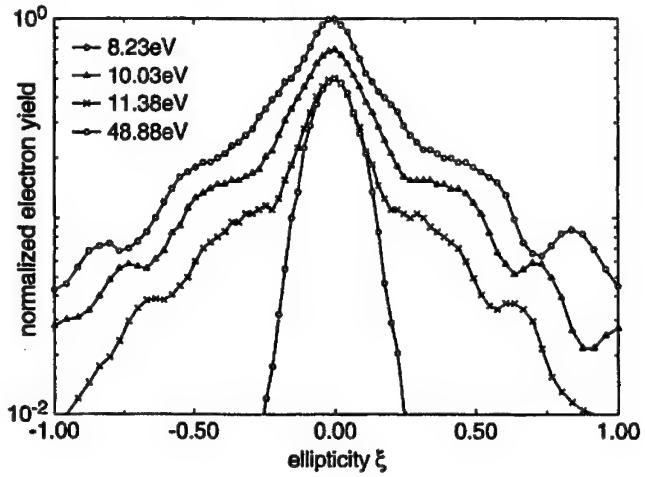
Here we report on a novel structure in the ellipticity distributions of the photoelectrons, i.e. the electron yield for a given electron energy as a function of the ellipticity of the laser polarization. In contrast to previously described effects, this structure cannot be explained by classical arguments. Actually, the effect owes its existence to a genuine quantum phenomenon: interference of electrons that reach the continuum at different times via tunneling .

We use high-repetition femtosecond dye-laser pulses with a duration of 50fs and an intensity up to 10^{14}W/cm^2 to produce ATI-electrons of rare gase atoms. The ellipticity of the laser polarization is controlled by a quarter wave plate with the big axis of the polarization ellipse always pointing in the direction of the electron detector of the high-resolution time-of-flight spectrometer.

The figure displays ellipticity distributions of Xenon at $1.2 \cdot 10^{14}$W/cm^2 for different photoelectron energies as parameters. The data are extracted from ATI-spectra which were recorded for various ellipticities of the laser polarization. As expected, the electron yield drops as the ellipticity is increased since the peak strength of the oscillating electrical field of the laser decreases. For the high-energy electrons the decrease in electron yield is very pronounced. This appears to be resonable since these electrons are known to originate from rescattering, i.e. a mechanism which stops working for increasing ellipticity.
The low-energy ellipticity distributions are much broader. However, superimposed on their general appearence there is a local maximum as well as one or several

"shoulders". The whole structure moves to lower ellipticities with increasing electron energy. A simple quantum mechanical model reproduces these phenomena and provides the interpretation that they are due to interferences of tunneling trajectories. Futhermore, there is an interesting connection to the problem of tunneling times which can be infered from the data for a dynamical tunneling problem for the first time.

Tunneling interference effects are *not* restricted to experiments with elliptically polarized laser light. Most probably they are responsible for many seemingly erratic features observed in calculations of high-harmonic generation and above-threshold ionization. In experiments, however, these features are washed out by power fluctuations of the laser pulses. In the ellipticity distributions the interference pattern shows up because the position of the interference minima as a function of ellipticity is relatively insensitive to intensity fluctuations.



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Towards a time-dependent density-functional description of multiphoton-ionization of helium in strong laser fields

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Abstract. In this work we address the problem of multiple ionization of atoms in strong laser fields (in the infrared and visible range). To this end we numerically solve the full, three-dimensional time-dependent Kohn-Sham equations for a helium atom in a strong 780nm laser field. Explicit density functionals for the calculation of ionization probabilities are developed. From the results we draw conclusions about the role of electronic correlation in the ionization dynamics and about the validity of present-day exchange-correlation potentials.

The advent of short laser pulse experiments has revealed evidence of a significantly enhanced production of doubly charged noble gas atoms [1]. In high-precision measurements covering a wide dynamical range of intensity dependent ionization [2,3], a "knee" structure in the double ionization yields of helium has been observed. Up to an intensity of roughly $3 \times 10^{15}\mathrm{W/cm^2}$, the double-ionization yields are *orders of magnitude* above the signal that one would expect from a "sequential" mechanism, in which the second electron only comes from the ionization of He^+. The He^+ and the He^{2+} curves saturate at the same intensity, suggesting that the ionization proceeds nonsequentially via a "direct" process where the amount of energy absorbed from the radiation field is shared among the two electrons. Perturbative methods [4] and the solution of theoretical models based on a simplified dielectronic interaction [5] underline the importance of time-dependent electron-electron correlation during the process.

The double-ionization measurements constitute the most distinct manifestation of electron correlation in the physics of intense laser-atom interactions, making indispensable a non-perturbative quantum mechanical description of interacting electrons in strong, time-dependent external fields. The full solution of the three-dimensional time-dependent Schrödinger equation for the helium atom in strong laser fields, however, is barely numerically tractable, even with the use of modern massively parallel computers [6–8]. In view of its computational simplicity, time-dependent density functional theory [9,10] suggests itself as a viable alternative. By virtue of the theorem of Runge and Gross [9], every observable can, in principle, be calculated from the time-dependent density. The latter is obtained from

$$n(\mathbf{r},t) = \sum_{j=1}^{N} |\varphi_j(\mathbf{r},t)|^2 \tag{1}$$

(N being the number of electrons) with orbitals $\varphi_j(\mathbf{r},t)$ satisfying the time-dependent Kohn-Sham equation

$$i\frac{\partial}{\partial t}\varphi_j(\mathbf{r},t) = \left(-\frac{\nabla^2}{2} + v(\mathbf{r},t) + \int d^3r' \, \frac{n(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|} + v_{xc}[n](\mathbf{r},t)\right)\varphi_j(\mathbf{r},t) \tag{2}$$

(atomic units are used throughout). This equation provides an in principle exact alternative to account for the fully correlated character of the problem by virtue of the time-dependent exchange-correlation potential $v_{xc}[n](\mathbf{r},t)$ which is a universal functional of the density.

We define ionization probabilities by means of a geometrical concept: By dividing the space $\mathbb{R}^3$ into two regions, the analyzing volume A (which has to be appropriately chosen), and its complement $B = \mathbb{R}^3 \setminus A$, the norm of the correlated two-particle wavefunction can be written as

$$1 = \int_A d^3r_1 \int_A d^3r_2 \, |\Psi(\mathbf{r}_1,\mathbf{r}_2,t)|^2 + 2\int_A d^3r_1 \int_B d^3r_2 \, |\Psi(\mathbf{r}_1,\mathbf{r}_2,t)|^2 + \int_B d^3r_1 \int_B d^3r_2 \, |\Psi(\mathbf{r}_1,\mathbf{r}_2,t)|^2 . \tag{3}$$

The second term (AB) in equation (3) is equal to the probability of finding one electron inside the volume A and simultaneously finding a second electron outside the volume A. This is interpreted as single ionization. In analogy, the third term (BB) in equation (3) is given the interpretation of double ionization. Clearly, for this interpretation to be valid, the analyzing volume needs to be large enough so that the bound-state population is well represented by the norm inside A. In terms of the pair-correlation function of helium

$$g(\mathbf{r}_1,\mathbf{r}_2,t) := \frac{2\,|\Psi(\mathbf{r}_1,\mathbf{r}_2,t)|^2}{n(\mathbf{r}_1,t)\,n(\mathbf{r}_2,t)} \tag{4}$$

which, by virtue of the Runge-Gross theorem, is a functional of the time-dependent density, the ionization probabilities of helium can be expressed as

$$P^0(t) = \frac{1}{2}\int_A d^3r_1 \int_A d^3r_2\, n(\mathbf{r}_1,t)\,n(\mathbf{r}_2,t) g[n](\mathbf{r}_1,\mathbf{r}_2,t) \tag{5}$$

$$P^{+1}(t) = \int_A d^3r\, n(\mathbf{r},t) - \int_A d^3r_1 \int_A d^3r_2\, n(\mathbf{r}_1,t)\,n(\mathbf{r}_2,t) g[n](\mathbf{r}_1,\mathbf{r}_2,t) \tag{6}$$

$$P^{+2}(t) = 1 - \int_A d^3r\, n(\mathbf{r},t) + \frac{1}{2}\int_A d^3r_1 \int_A d^3r_2\, n(\mathbf{r}_1,t)\,n(\mathbf{r}_2,t) g[n](\mathbf{r}_1,\mathbf{r}_2,t)\,. \tag{7}$$

The described density functional approach thus involves two basic approximations:

1. The time-dependent density is calculated using some approximate exchange-correlation potential.
2. The functional dependence of the pair-correlation function g on the density n in equations (5) – (7) is only approximately known.

We have explored several approximations for the functionals $v_{xc}[n](\mathbf{r},t)$ and $g[n](\mathbf{r}_1,\mathbf{r}_2,t)$ and culculated the double ionization yields of helium as a function of intensity. It turns out that none of the presently available functionals is able to reproduce the measured "knee" structure. All these approximations have in common that they are local in time, i.e. the exchange-correlation potential at time t only depends on the density at the very same point in time. The true functional, however, should include memory effects, i.e. the exchange-correlation potential at time t should depend on the densities at all previous times t'. We propose a new approximation for the exchange-correlation potential which includes such memory effects [11].

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Phase-dependent harmonic emission with ultrashort laser pulses

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In a recent experiment performed at the Technical University of Vienna [1], it has been demonstrated that Helium exposed to an extremely short (about 2 cycles) and intense (5×10^{15} Watt/cm^2) pulse generates high order harmonics well into the so-called water window. This opens the route to important applications, in particular in biology. Besides, it also provides an effective way to produce subfemtosecond harmonic pulses.

In this experiment, the key parameter for optimizing the X-ray source for maximum brightness at high photon energies is the initial phase of the laser. However, this phase which affects significantly the X-ray flux in the cutoff region is not controlled experimentally. The purpose of the present contribution is to analyse in detail the sensitivity of the harmonic emission process to this initial phase of the laser and to address the question of probing this phase in a single shot experiment.

By solving numerically the corresponding 3-dimensional Schrödinger equation, we show that the harmonic spectra are in the present conditions extremely sensitive to the initial phase of the laser. Depending on this phase, the harmonics in the cutoff region are resolved or not. Furthermore, the position of the cutoff itself varies with this phase and the so-called 'plateau' region exhibits two well distinct parts; in the low frequency part, we observe well defined harmonics while the high frequency part consists in a series of broader peaks which are not any more separated

by twice the laser frequency. These results are explained in terms of both quantum and classical dynamics.

Finally, we show that this phase sensitivity may be exploited in order to probe the initial laser phase for ultrashort pulses. The behaviour of a given high order harmonic as a function of the initial phase is very characteristic. The amplitude of the harmonics exhibits a deep minimum whose position depends on the order of the harmonic. This result does not depend significantly on the pulse shape provided that both the pulse duration and the peak intensity are the same. As a result, it exists a relation between the initial phase of the laser and the number of photons emitted within a narrow frequency bandwidth. Our discussion about this new method of diagnosis takes into account propagation effects.

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DYNAMICS OF TWO ELECTRON QUANTUM SYSTEM IN A STRONG LASER FIELD

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Abstract. The dynamics of the one-dimensional negative hydrogen ion H^- in a strong laser field is studied. Different approarches (single electron model, Hartree and Hartree - Fock approximation) are compared with the exact numerical solution of the two-particle non-stationary Schroedinger equation. The probabilities of single and double ionization are calculated for different frequencies and intensities of laser radiation. Strong electron - electron correlations are found to exist for the ground state and dynamics of double ionization. The stabilization against ionization is investigated for a two-electron system. The photoelectron energy spectra for single electron ionization process are analyzed.

The ionization dynamics of one of the simplest multielectron systems - negative hydrogen ion is investigated numerically. The main goals of our research are the following:

1. to examine the validity of single electron model for ionization dynamics of the two-electron system in a strong laser filed;
2. to study the influence of electron - electron correlations on the ionization dynamics of the system;
3. to investigate the possibility of the stabilization regime in the multielectron system;
4. to study which mechanism of the double ionization (direct or sequential) takes place in the strong field limit.

To answer these questions different approarches (single electron model, Hartree and Hartree - Fock approximation) are used to investigate the evolution of the quantum system in the electromagnetic wave field. The obtained results are compared with the exact numerical solution of the two-particle non-stationary Schroedinger equation in a strong laser field.

Two-particle numerical calculations are performed using the one-dimensional smoothed Coulomb potential [1] with the smoothing parameter of 0.92 A choosen for the electron - nuclear and electron - electron interaction.

The only bound state with inner and outer electron is found to exist in such a potential. The ionization potential of our system is approximately 1 eV. It's quite close to

the ionization potential of the real three-dimensional and model one-dimensional single-electron negative hydrogen ion [2].

The wave function derived from the non-stationary Schroedinger equation is used to calculate the probabilities to find the system in the bound state after the laser pulse action and the probabilities of the single- and double-electron ionization. Also the electron energy spectra for single electron ionization are calculated.

The simulations are performed for the laser frequencies corresponding to laser quanta $1 - 15$ eV and laser intensities of $10^{12} - 10^{15}$ W/cm^2. The laser pulse is of trapezoidal envelope with turn-on (-off) time of two optical cycles and the plateau duration of five optical cycles.

Several interesting results are obtained from our simulations.

1. Strong electron - electron correlations are found to exist both for the initial ground state and the dynamics of double ionization. These correlations can not be described in terms of self-consistent potential approarches of Hartree or Hartree -.Fock.
2. Single electron model for the H^- system is shown to be valid for the quite low frequencies when it is possible to neglect the interaction of the laser field with the inner electron. In this case stabilization against ionization is observed and the thresholds of stabilization calculated in the frames of single and double electron models are found to coincide with each other. For high frequencies ($\hbar\omega \geq 5$ eV) the laser field is shown to influence strongly upon the inner electron even in the case of quite low intensities. As a result the single electron approximation fails and the stabilization regime is destroyed.
3. It is found that double ionization of H^- is the result of the competition of the direct and sequential mechanisms of the process.
4. The multipeak structure of the photoelectron spectra for the single electron ionization regime is observed. The structure obtained appears to be a result of the single - electron ionization accompanied by simultaneous excitation of the hydrogen atom formed during ionization process. The probabilities of such an excitation can be interpretered in terms of absorbtion of different number of photons and ionization of outer or inner electron of the system.

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Laser-induced alignment of molecules on a vibrational timescale

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Abstract. A pronounced anisotropy is observed in the angular distribution of the ionic fragments from multiphoton dissociative ionisation of diatomic molecules. Calculations within the field-ionisation, Coulomb explosion model show that the experimental I_2 results (pulses of 50 fs at an intensity ~ 10^{14} W cm^{-2}) can be explained without invoking reorientation of the molecular axis. The fragments of the lighter H_2 and N_2 molecules, on the other hand, show clear signs of being forced into alignment.

When diatomic molecules are subjected to intense laser pulses (> 10^{13} W cm^{-2}), multielectron dissociative ionisation occurs and the ionic fragments have kinetic energies that are typically about half of that expected from Coulomb explosion at the equilibrium internuclear distance of the molecule. Furthermore, the ions are predominantly ejected along the *E*-field of the linearly polarized laser radiation.

The classical field-ionisation, Coulomb explosion (FICE) model (Posthumus *et al* 1996) allows us to calculate the minimum laser intensities that are required for over-the-barrier ionisation as a function of internuclear separation. The complex behaviour at the critical internuclear distance, R_c, when the central potential barrier impedes the adiabatic adjustment of the molecule to the laser *E*-field, is described in simple terms by a Stark-shift of the localized electron.

The enhancement of the ionisation probability at R_c is strongest for molecules aligned along the polarization direction. We have investigated to what extent this phenomenon is responsible for the highly anisotropic angular distributions (Posthumus *et al* 1998).

With the FICE model, we can calculate threshold intensities, which are dependent on the angle between the polarization and the molecule axes. In the laser focus, these threshold intensities define shells; the higher the threshold intensity, the smaller the volume of the shell. Figure 1 shows the relative sizes of the volumes of the $I^+ + I^{2+}$ shell as a function of angle and for a number of laser intensities. If no laser-induced rotation of the molecule axis takes place, then one would expect the angular distributions of the fragments of this channel to look very similar to these curves. Given

the measure of agreement with the experimental results shown in figure 2, we conclude that laser-induced reorientation is not involved to any great extent when I_2 molecules are field ionized by 50 fs laser pulses.

The H_2 and N_2 molecules, on the other hand, are much lighter and therefore more susceptible to reorientation. Furthermore, due to their higher ionisation potentials, these molecules are more resistant to field-ionisation and Coulomb explosion and can therefore be subjected to higher laser *E*-fields and torques before they dissociate.

The angular distribution of the $H^+ + H^+$ channel is considerably sharper than any that we have measured for iodine. We therefore concluded recently (Thompson *et al* 1997) that hydrogen is considerably reoriented by sub-100 fs laser pulses. Clear signatures of dynamic laser-induced alignment are a narrowing of the angular distributions with increase in laser intensity (however, remaining below the saturation intensity) and an absence of fragments perpendicular to the laser polarization at all laser intensities (Posthumus *et al* 1998)

Figure 1: FICE model

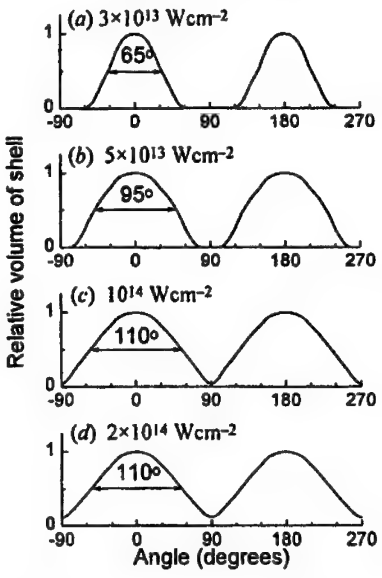
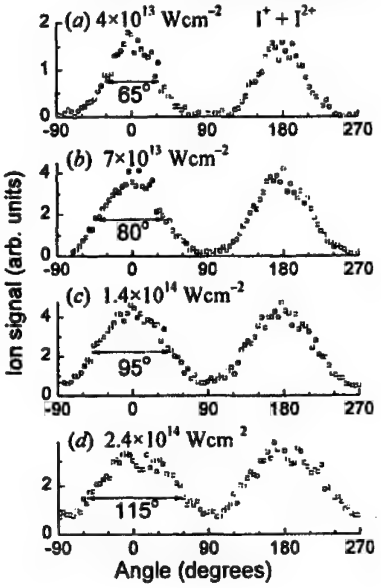


Figure 2: Experimental results



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Posthumus *et al* 1998 submitted to *J. Phys. B*

Relativistic Laser Plasma Interaction by Multi-Dimensional Particle-In-Cell Simulations

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Development of relativistically strong short laser pulses [1] has opened a new dimension in physics of laser plasma interaction. This physics is essentially kinetic, strongly nonlinear, and still far from complete theoretical understanding. From another side, a tremendous progress in the computer technology and development of Massively Parallel Processing (MPP) computers with TeraFlop performance has allowed for the first time the direct simulation of actual laser plasma experiments by 3D Particle-in-Cell (PIC) codes [2-4]. The PIC codes are based on fundamental equations for the particles and fields dynamics and provide the most detailed kinetic description of plasmas. Considering a 3D PIC simulation one can speak about a numerical or "virtual" laser plasma experiment. Here we report on results obtained with 3D electromagnetic relativistic PIC code **VLPL** (Virtual Laser Plasma Laboratory) developed at Garching [5].

A regular study of energy spectra of accelerated electrons and ions for different laser powers ranging from TeraWatt to PetaWatt is presented. The results of the 3D PIC simulations are compared with actual experiments. We discuss acceleration of background plasma electrons to multi-MeV energies by direct laser push, and present the novel "magnetic field assisted" or "B-loop" acceleration mechanism [3]. The self-generated azimuthal magnetic field [2] confines the electrons ponderomotively scattered aside from the laser focus, and returns them

for the next acceleration stage. Energy gain in this step-like process piles up to many ponderomotive potentials. We compare this mechanism with the wake-field acceleration.

We study dynamics of ion channel boring and self-generation of 100 MGauss magnetic fields in under- and overdense plasmas. A collisionless ion shock wave outgoing in the radial direction is formed. It consists of ions accelerated to MeV energies in the process of the channel explosion. In the case of a deuterium plasma, these ions produce fusion neutrons with a characteristic energy of 2.45 MeV. Such neutrons have been detected experimentally at MPQ [6].

We show that the conversion efficiency of the laser power in the fast electrons can be as high as 40through the overdense plasma is self-organized in a form of magnetized jets. We find a high collective stopping power in a $10\times$ overcritical plasma because of an anomalous resistivity. This physics is crucial for the Fast Ignitor concept [7,8] in Inertial Confinement Fusion, as well as for the plasma based particle acceleration.

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Alteration of Nuclear Beta Decay by Non-Nuclear Strong Fields

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We explore the possibility of effecting substantial changes in the rates of "forbidden" nuclear beta decay by exposing the nuclei to very intense low frequency electromagnetic fields. Lifetimes of forbidden beta decays are very long because of the violation of quantum selection rules on angular momentum and/or intrinsic parity. To accelerate such decays it is not necessary to transfer any energy to the nucleus, only angular momentum and/or parity, possessed in abundance by strong fields even at low frequency. The real question is whether effective coupling between the long-wavelength field and the very small nucleus can be achieved.

We identify two explicitly strong-field mechanisms that can accomplish this coupling, and evaluate their effects on the decay lifetime. One of these mechanisms arises from the figure-8 motion associated with the response of a charged particle to an intense plane-wave electromagnetic field. The proportions of the figure-8 motion are a function only of the usual free-electron intensity parameter encountered in all intense-field plane-wave free-electron problems. Invariance of the proportions is true independently of the wavelength of the field. Local angular momentum associated with this motion is significant. The other mechanism for transferring angular momentum from the field to the beta decay process comes from the strong-field dressing of the initial and final nuclear states. The effectiveness of this coupling mechanism arises from the fact that the charges of the initial and final states are different. The governing intensity parameter for this process is similar to that from the first coupling mechanism, but smaller by a factor depending on the ratio of the nuclear radius to the electron Compton wavelength.

The transition amplitude for accelerated beta decay can be written for V-A weak interactions in terms of nuclear wave functions that are not initially specified. Subject only to a limiting procedure dependent on the low frequency of the field as compared to the rest energy of the electron, we exhibit matrix elements that show clearly how the field-modified transition amplitude is related to the no-field case. The two mechanisms described above are plainly evident, and produce important alterations in the decay rate. Full analytical evaluation of transition rates with simple model wave functions is carried out for a simplified scalar beta decay. Important acceleration of forbidden beta decay should be possible.

We examine the flaws in previous treatments of this problem. Specifically, an earlier negative conclusion about the prospects for accelerating forbidden beta decay arose directly from the use of a circularly polarized external field. We show why linear polarization is essential for both of the basic coupling mechanisms.

Potential practical applications of this process to high-level radioactive waste disposal and to primary energy production are discussed.

Relativistic effects in a plasma driven by a laser field.

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The availability of lasers of increasingly intensity allows the direct observation of strong relativistic effects in the laser-plasma interaction. Several new effects appear, connected with the non-linear electron motion at such high intensities.

We would like to analyse theoretically a number of strong non-linear surface effects, that can appear in the relativistic regime. Among them, we will study the reflection of an ultra-high intensity laser beam on a plasma slab. For a normal incident laser, the magnetic field component of the Lorentz force induces an oscillating movement perpendicular to the plasma surface. We will show how the reflection in this oscillating surface distorts the incident field shape, leading to a train of subfemtosecond pulses in the reflected field.

We will also analyse the possibility of electron reorganisation at the plasma surface, when one or two intense lasers impinge on it. We will show, that, grating-like structures can appear at the plasma surface for certain conditions, and we will discuss the electric field reflected under these circumstances.

1D3V Particle-In-Cell codes results are to be presented. These numerical simulations confirm the theoretically predicted features of the inhomogeneities of the electron plasma.

H_2^+ photodissociation and Coulomb explosion; a high resolution study of these processes

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We present recent progress in investigating the decay of H_2 in ultrashort high intensity light pulses. We put special emphasis on high resolution photoion kinetic energy spectroscopy. Experiments are done in a cold molecular beam formed in a free jet expansion to get rid of the thermal kinetic energy spread in the gas phase. Angle resolved kinetic energy distributions are measured with the time of flight technique. In the spectrum shown below the energy resolution is estimated to be better than $\approx$ 15 meV at 1 eV ion kinetic energy, limited only by the time binning used. The hydrogen molecules are excited by the radiation of a Ti:Sapphire laser system. It delivers pulses with a pulse width of $\approx$ 65 fsec, and a pulse energy of up to 3 mJ at 790 nm center wavelength. The laser beam is focused onto the molecular beam to reach intensities in the range between 10^{14} and a few times 10^{15} W/cm^2.

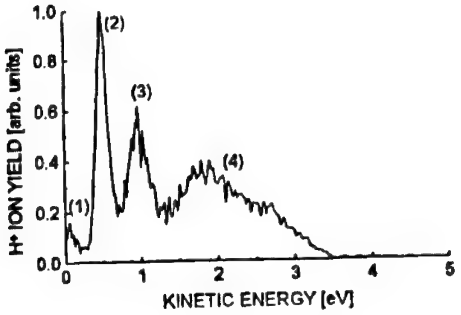

Figure 1: H^+ ion kinetic energy distribution at 790 nm excitation wavelength and 65 fsec light pulse width. The light pulse intensity is 8×10^{14} W/cm^2. For further details see the text.

Fig. 1 shows a representative H^+ ion kinetic energy distribution. It was taken at a light pulse intensity of 8×10^{14} W/cm^2. The spectrum shows four significant features ((1) - (4) in Fig. 1). (1) and (2) have their origin in photodissociation of H_2^+. This is similar to results found at completely different and nearby excitation wavelengths [1 - 4]. The process giving rise to line (1) is bond-softening dissociation of H_2^+ while line (2) is formed by above threshold dissociation (ATD) [3,4]. The width of the prominent line (2) is $\approx$ 180 meV (FWHM). It is slightly dependent on light intensity while its position does not depend on light intensity. Corresponding lines at identical energies and with identical properties appear if D_2 is used instead

of H_2. The bandwidth of the laser radiation is expected to make a main contribution to the width of line (2) ($\approx$ 80 meV). The intrinsic width of this line can therefore be estimated to be below 100 meV. Taking the H_2^+ vibrational quanta into account this means that it is only one single state which dissociates by ATD and not a Franck-Condon distribution over H_2^+ vibrational levels (expected by non-resonant MPI of H_2) as it was assumed in refs. [3,4]. If one wants to assign unperturbed H_2^+ initial vibrational states to lines (1) and (2) v = 2 fits to the center of line (2) (assuming 2-photon ATD) and v = 5 to line (1) (assuming 1-photon dissociation). Neighbouring vibrational states give rise to ions with a kinetic energy outside the range of the estimated intrinsic width of lines (1) and (2). This assignment neglects rotational energy of the molecular ion. Since the positions of lines (1) and (2) do not show a significant dependence on light intensity we suspect that they are formed at a fixed instantaneous intensity within the light pulse.

Coulomb explosion after charge resonance enhanced ionization (CREI) of H_2^+ is responsible for the broad feature (4) in Fig. 1 [3 - 6]. Its shape depends on the light pulse intensity. As expected the high energy cutoff shifts to higher energy with increasing light intensity. If D_2 is used instead of H_2 the corresponding structure appears in the same range of internuclear separations with a very similar shape but with a high energy cutoff which is usually steeper for D_2 than for H_2. This can be understood in terms of ionization from a dissociating molecular ion. The dissociation velocity for D_2^+ is smaller than for H_2^+ at the same internuclear separation thus leading to more efficient photoionization at smaller internuclear distances.

A new structure observed here for the first time is line (3) at 1.0 eV. Its position in the spectrum depends on the isotopomere. For D_2 the corresponding structure appears at a higher kinetic energy (1.2 eV). This seems to indicate that nuclear dynamics is strongly involved in its formation. We are led to assume that this feature is formed by Coulomb explosion after photoionization at internuclear separations beyond the critical distance for CREI ($\approx$ 7 a.u.). The internuclear separation where H_2^+ has to be photoionized to give rise to line (3) can be estimated to be $\approx$ 20 a.u..

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Attosecond pulse trains from a solid surface

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Recently there has been a quest for achieving pulses of electromagnetic field of very short duration. There is an attempt to break the femtosecond barrier. Many proposals of using to this end high harmonics generated during ionization of atoms in a gas phase have been put forward and then where found to be hard to realize because of an inherent lack of coherence between different harmonic components of the emitted light. High harmonics are also generated in the scattering of a powerful short pulse off a surface of a solid. Good qualitative picture of this scattering is offered by an oscillating mirror model [1]. According to this model, the leading edge of the pulse rapidly ionizes the atoms near the surface and the liberated electrons start moving under the influence of the impingent light. A mirror is formed. If the electronic motion is relativistic, then, even at normal incidence, there is a component of this motion perpendicular to the surface. This oscillating mirror gives rise to a spiky character of the reflected light signal [2]. This is similar to a sonic boom produced by an aircraft approaching the speed of sound. The finding has been substantiated by a suitable coarse grained calculation, known as PIC code. As it turns-out, also in this case we are limited by an imperfect coherence of the harmonics. However the experiment done with ultra thin film is expected to produce harmonics which are coherent down to a wavelength comparable to the thickness of the film. Thus using a film which has thickness of 0.1 of the wavelength of the ionizing pulse one should be able to produce spikes of electromagnetic field which are only 0.1 of the period of light used. At the end I will also comment on the possible methods of diagnosing this spiky light signal.

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Dense plasmas generated by high-intensity lasers

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Abstract:

The interaction of high intensity (10^15 - 10^18 Wcm^-2) femtosecond laser radiation with solid targets is reviewed. Experiments demonstrating the generation of matter at solid density and temperatures of 10^7 K are discussed. Such plasmas begin to exhibit features in their optical properties dictated by strong coupling between the particles. Absorption mechanisms are due to collective effects in the interaction of light and matter. Temporally resolved measurements of amplitude and phase of the reflected laser light indicate accelerations up to the 10^19 ms^-2 in the plasma.

Laser-driven helium

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Rapid developments in high-intensity laser technology over the past decade has provided experimentalists with a source of polarized monochromatic electromagnetic radiation with which to violently agitate even the innermost electrons of an atom or molecule [1]. The violent interaction takes place over such a short time scale ($\sim$ 20 fsec) that the wavefunction for the atomic electrons evolves quickly and has no opportunity to be dominated by any stationary character. Thus the theorist is presented with an opportunity to study atomic electron dynamics far from equilibrium. Electron-electron interaction and, for laser intensities greater than 10^{18}W/cm^2 relativistic effects, play a very different role than in stationary atomic processes (electron-atom scattering, for instance) since now there is no longer infinite time for interactions to be equilibriated. In fact we have found even the electronic wavefunction of a single electron atom to evolve in an unusual manner with its diminishing inner part moving under the combined influence of the attractive nucleus and the laser field, but with its growing outer part moving almost as the wavefunction of a free charged particle in the laser field alone.

Helium, with just two electrons, is the simplest atom where electron-electron interaction comes into play. We have recently embarked on a theoretical/computational study of the response of this atom to a high-intensity, linearly-polarized laser pulse. With such a pulse, the electronic motion has just 5 degrees of freedom -the overall component of angular momentum along the polarization direction is still conserved. The foundation of our study [2] has been to integrate directly the time-dependent Schrödinger equation for a wavefunction solution that spans all five spatial dimensions i.e. both electrons of the atom are treated on an equal footing.

For the past decade supercomputers have slowly been approaching the performance necessary but it has been the advent of the Cray T3D that has made this level of calculation possible. The code we have developed handles the three angular variables by a basis-set expansion over partial-waves and the radial variables are represented over a finite-difference mesh. Because the response of an atom extends over such a large dynamic range (typically 10 orders of magnitude) the resulting coupled partial-difference equations must be solved to a much greater level of accuracy (about 10 decimal places) than is typically required in engineering applications.

One of the primary applications of the full numerical integration, is to provide support in the design of reduced dimensionality models of many-body dynamical systems, in this case laser-driven helium. We introduce a new single active electron (SAE) model of laser-driven helium based on a Coulombic screening potential. The screened potential consists of the helium ($Z = 2$) Coulomb potential added to a term depending on radial distance r that represents the screening of one helium electron by the other i.e. it takes the form $(Z - \mathrm{screen(r)})/\mathrm{r}$. The function screen(r) has a similar functional form to the screening predicted by frozen-core time-dependent Hartee-Fock (FC-TDHF), but uses information about the final states of the multiphoton transition, rather than just the initial state.

Figure 1 shows results of the full FD helium calculation (labeled helium) at $\omega = 0.21$ a.u., our new SAE model (labeled V_{eff} potential), as well as from 2 standard SAE models, FC-TDHF and an

effective Coulomb potential model that has the same ionization potential as neutral helium. The FC-TDHF screened potential gives the wrong ionization rate by a factor of 3, the Coulomb by a factor of 6.

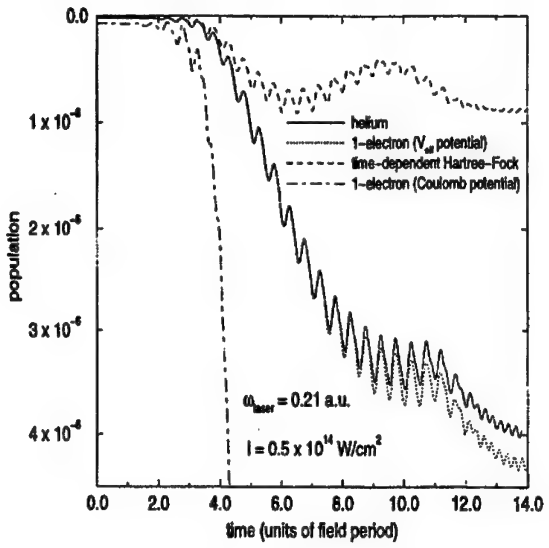

Figure 1: Population 8 Bohr radii from the nucleus and beyond during excitation with a 14 field period pulse. The pulse is ramped on over 4 field periods and ramped off similarly.

We have work progressing in a number of areas in addition to those touched on above. Some of these are:

- Analysis of the time-evolving, multi-dimensional wavefunction using scientific visualisation techniques
- Study of one-electron/two-electron ionization branching ratios
- Extension of our approach to handle lower-frequency and higher-intensity laser pulses

The presentation at the meeting will report on several aspects of this overall project.

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STABILIZATION OF THE ATOMIC SYSTEM IN A STRONG LASER FIELD AND THE KRAMERS-HENNEBERGER APPROACH

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Abstract: The ionization of the quantum system with short-range potential by linearly polarized laser field is studied numerically in a wide range of laser intensities and frequencies. The interpretation of the dynamics is performed in terms of both Kramers-Henneberger eigenstates and field-free atomic states. The exact solution is analyzed to see the presence of one or another set of eigenfunctions and to determine what potential (atomic or Kramers-Henneberger potential) is physically more appropriate to describe the ionization process. The justification of Kramers-Henneberger approach is examined especially for low laser frequencies and the low limit on the laser intensity is found to exist. The low frequency stabilization is shown to occur only if the Kramers-Henneberger approach is physically correct and does not take place beyond the limitations of validity.

The adiabatic stabilization [1,2] is known to be investigated more convenient in the Kramers-Henneberger (KH) frame [3]. In this case the atomic Hamiltonian is transformed to KH Hamiltonian that consists of the time-averaged part (KH potential) and harmonics of the KH potential. In the case of high frequencies and strong field the harmonics can be taken into account in the first order of perturbation theory [2]. The corresponding first-order lifetime of KH states is shown to be an increasing function of the light intensity beyond some critical intensity value P^* [2,4]. Thus, ionization of atom is considered to be suppressed and the intensity P^* is the threshold of stabilization. The stabilization threshold is demonstrated to fall down with the decrease of laser frequency [4,5]. The problem arises in the case of low frequencies: the threshold of stabilization tends to zero and no limitation appears.

To solve this problem, the ionization of the quantum system with short-range potential by electromagnetic laser field is investigated numerically in a wide range of laser intensities and frequencies. The 1D nonstationary Schrödinger equation is solved in the field-free atomic frame, but both bound-state dynamics (of the KH time-averaged Hamiltonian and of the field-free Hamiltonian) is examined. The ionization probability

and photoelectron spectra are obtained in the after-pulse regime. All the results are analyzed to determine what basis and what potential is physically more appropriate for correct description of the ionization process.

In the case of high frequency $\hbar\omega > I_{atom}$, the ionization of the system is shown to be described well in terms of KH eigenstates: the mean-electron coordinate is shown to be very close to the position of the free electron in electromagnetic field; the photoelectron energy is found to correspond to the ionization from the KH potential; the KH eigenstates appear to be depleted gradually during the laser pulse in contrast to the population of atomic bound states. The stabilization regime is found to occur at rather high intensities, when the KH eigenstates become more and more stable with the increase of the field strength. The stabilization threshold is confirmed to be proportional to the laser frequency cubed: $P^* \sim \omega^3$, according to the Refs [4,5].

In the case of low frequencies ($\hbar\omega << I_{atom}$) there is the regime of ionization at rather low intensities, that can be described well in terms of field-free atomic Hamiltonian. In this case, the first-order perturbation theory on the harmonics of KH potential does not seem to be correct and the KH approximation does not appear to be valid. Thus, the low-frequency validity of KH approach is limited by certain intensity value, that is found to be very close to the threshold of the barrier suppression ionization P_{BSI}. For very low (IR) frequencies, the stabilization regime seems to appear as soon as KH description become physically correct. The stabilization threshold in dependence on laser frequency is shown to confirm the analytical prediction about the decrease of the slope in the low-frequency limit [5] and to demonstrate the asymptotic behaviour with the asymptotic limit equal to P_{BSI}.

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Theory of two-color pumb-probe determination of multiphoton ionization dynamics

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We show, through numerical simulations, that it is in principle possible to follow in time the structure and the population dynamics of an atomic system "dressed" by a strong time varying laser field [1]. The proposed time-resolved spectroscopy scheme exploits the properties of the currently developed sources of coherent XUV radiations, generated via high order harmonic conversion. With pulse durations within the femtosecond range, it is possible to conceive two-colour pump-probe schemes which would help to shed light on issues currently under discussion about the dynamics of strong field photoionization.

In the two-color pump-probe scheme considered here, one records the photoelectron spectra produced when atoms are submitted to an intense IR laser, while a short UV pulse scans the longer laser pulse. Atoms can then be ionized via the joint absorption of the UV photon and of one (or several) photon(s) from the laser, the process taking place in addition to standard Above Threshold Ionization (ATI). By monitoring the changes in the positions and magnitudes of selected photoelectron lines originating from such two-color process, this experimental scheme can provide a time-dependent picture of the ac-Stark shifts and populations of atomic dressed states in the strong laser pulse.

The simulations have been performed by numerically solving the Time-Dependent Schrödinger Equation for a 1-D 'soft-core' Coulomb potential, submitted to these two distinct fields.

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POSTER PRESENTATIONS

Mechanisms of Atomic and Nuclear Processes Stimulation in Strong Field of Laser Produced Plasma.

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Abstract
The main results of investigations devoted to atomic and nuclear processes induced by electromagnetic action of super strong fields in a laser-produced plasma on atoms are presented. It is demonstrated that transformation of such fields by atomic structures leads to the generation of magnetic fields in an atom, which destroy the internal structure of low-lying electronic shells and give rise to wave collapse, or "nucleation", of the fields with subsequent strong action on nuclei. The uniqueness of processes that occur in a plasma produced under the action of high power ultra short pulse laser radiation upon a solid target causes the specific effect of this plasma on atomic and nuclear structures. In the framework of self-consistent problem that takes into account the atomic nature, this action crucially differs from the action of a high-power laser pulse on a stripped nucleus. With certain conditions, an atom becomes an instrument effectively transforming the energy of initial laser radiation in to the fluxes of radiation localized on a scale close to the size of nucleus and capable to stimulate nuclear processes. This is the basis of the possibility of controlled electromagnetic stimulation of atomic and nuclear processes in a laser produced plasma.

Summary
We developed the theory of the interaction of high intensity (> 1016 W/cm2) ultra short (< 10-12 s) laser radiation pulses with matter. This study continues the cycle of our investigations devoted to the electromagnetic stimulation of atomic and nuclear processes in a laser produced plasma – processes associated with the development of kinetic plasma instabilities within a broad range of spatial scales from characteristic sizes of the skin layer to interatomic sizes [1-4].
It is demonstrated that the development of Weibel instabilities responsible for the generation of strong magnetic fields in a laser produced plasma gives rise to a small scale structure of vortex magnetic fields, which efficiently interacts with atomic electronic shells. We analyzed this interaction using the nonlinear Schrodinger equation. Solutions to this equation display singularities. The physical meaning of these singularities can be understood in terms of the wave collapse of the fields and strong action on atomic nuclei. Such effects leads to the stimulation of artificial radioactivity and may allow under definite conditions nuclear fusion even for nuclei heavier than nuclei of hydrogen isotopes.
We consider for the first time the stability of atomic electronic shells under the action of super strong magnetic fields with allowance for the internal structure of nuclei. Our analysis demonstrated that the self-consistent problem concerning the transformation of laser radiation by matter should be solved with allowance for the excitation of nuclei. We developed a physical model of the excitation of nuclei under conditions when atoms transform electromagnetic fields in a laser produced plasma.
The results of the atom stability plasmas theory at stochastic action of the high frequency external fields are as follows:
- in the framework of the linear and quasilinear theories atom fields instabilities with the wavelengths of the order of atom size (r0 = 5(10-9 cm and in the wide frequency range 1015 < (< 1018 sec-1 from plasmas frequency up to tunnel ionization frequency were obtained;
- the energetic conditions for ionizing decay of the atom external shells were obtained; in particular, touching upon the diffusion character of ionization process, in this case the interest towards it is connected to the research of the atomic electron shell rebuilding as a result of which the action on the nuclei takes place; the stochastic character of the processes in atom at strong electromagnetic determinate fields action on it is in the basis of this mechanism;
- in the framework of the quasilinear theory the dynamics of atom shells decay at stochastic fields action times (10-15 sec was described; electromagnetic fluxes from the atom at its decay exceeding 1017 W/cm2 were evaluated;
- the mechanisms of "fast particles" generation with energy above 10 MeV and high acceleration tempo were analyzed;
- the dynamic of electron continuum creation and its structure in the form of the vortical fields were studied;

- the effects of super strong magnetic fields generation above 10 MGs were investigated;
- the mechanisms of the SHF-radiation and hard Roentgen generation were analyzed.

The developed theory allowed us to propose and perform experiments on the detection of nuclei reactions under conditions close to those analyzed theoretically.

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Interplay of electron correlation and intense field dynamics in double ionization of atoms

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A surprising result of a series of recent multiphoton ionization experiments has been the observation of a very large probability of double ionization of He (e.g. [1]) and multiple ionization of other rare gases (e.g. [2,3]) in intense linearly polarized laser fields, that exceeded the earlier expectations based on a step-wise (sequential) ionization process, by *many* orders of magnitude. Here we show, how the dynamics of double ionization of atoms depends on an interplay of electron correlation and non-perturbative field interaction.

By a systematic analysis, using the so-called 'intense-field many-body S-matrix theory' (IMST) [4-7], we could identify a dominant Feynman diagram, given in Fig. 1, that shows the following mechanism of double ionization: reading the diagram from the bottom upward, we see that one electron absorbs the photon energy ('$-*$') from the laser field by a virtual above-threshold ionization process (t_{ATI}, panel a, that also includes rescattering of the electron with the screened potential of the residual ionic core, V_s) and shares it with another electron via the electron-electron correlation interaction, $V_c = 1/r_{12}$, (t_{corr}, panel b), until both of them have enough energy to escape together from the binding force of the nucleus, with momenta $\mathbf{k}_a$ and $\mathbf{k}_b$. Based on this diagram we have derived a simple mathematical formula to analyse the experimental data obtained for double ionization of atoms as a function of laser intensity.

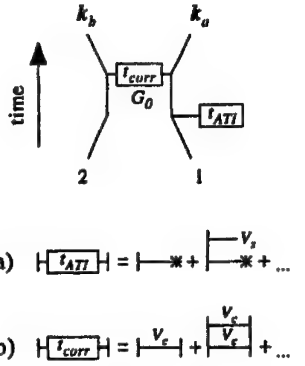

Fig. 1: Leading Feynman diagram for laser-induced double ionization of atoms. The lines stand for the states of the two atomic electrons, 1 and 2. t_{ATI} is the T-matrix for a virtual ATI-like process (panel a), and t_{corr} is the T-matrix for the e-2e transition (panel b).

A comparison of the present calculations and the experimental data for He atom is found to agree remarkably well at five different frequencies and all intensities measured, for both single and double ionization, including the ubiquitous 'knee' structure. In Fig. 2(a) the theoretical and experimental ion yields at $\lambda = 780$ nm (expt. [1]) are shown for the single ionization (He^+ yield: experiment, '+'; theory, left hand solid curve) and the double ionization (He^{2+} yield: experiment, '×'; theory,

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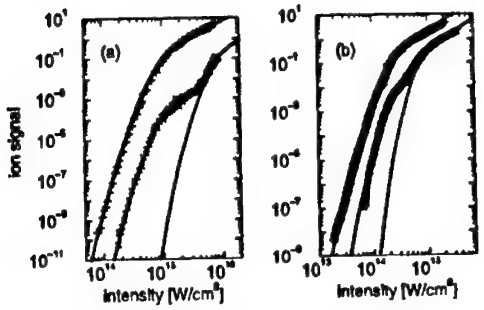

Fig. 2: Comparison of single and double ionization in He for $\lambda = 780$ nm (panel a, expt. [1]) and in Ar for $\lambda = 800$ nm (panel b, expt. [3]). Yield of singly ionized atom: exp., '+'; theory:, left hand solid curve; yield of doubly ionized atom: exp., '×'; theory, right hand solid curve; contribution of ionization of singly ionized atom, dotted curve.

right hand solid curve). Also shown is the calculated contribution to the He^{2+} signal from ionization of the He^{+} ion (dotted curve). It can be seen that the large probabilities (compared to the step-wise contribution) at $\lambda = 780$ nm, as well as at three other wavelengths ($\lambda = 745$ nm, 617 nm and 614 nm), are due to the combined effect of non-linear field interaction and electron correlation. This is in contrast to the double ionization signals at $\lambda = 248$ nm [8], that show no sign of the presence of a 'knee' structure. Our analysis shows that at the latter wavelength the He^{2+} signal is dominated entirely by the step-wise process. Finally, we have compared the theoretical results and the experimental data [2,3] for Ar (Fig. 2(b)), Kr and Xe at $\lambda = 800$ nm. Again a good agreement between the theory and the experimental data is found over the entire intensity range including the 'knee' structure. This work was partially supported by DFG (Bonn).

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TWO-COLOR PHOTODETACHMENT IN THE PRESENCE OF AN INTENSE LOW-FREQUENCY RADIATION FIELD

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We report on the photodetachment of a negative ion irradiated by two weak fields with frequencies ω_1 and ω_2, in the presence of a more strong low-frequency radiation field at frequency ω_L . The fields at frequencies ω_1 and ω_2 are assumed to be so weak that the absorption of more than one photon of each field is negligible. The low-frequency field is chosen so intense that the exchange of many photons during the photodetachment event is allowed, though, due to its low frequency, the probability of direct photodetachment by multiphoton absorption is negligibly small. By denoting with p such an integer that $\omega_1 - \omega_2 = p\,\omega_L$, the results of our calculations may be summarized as follows. When p is odd, angular distributions of the emitted electron, for a fixed value of their energy, result that show a polar asymmetry that depends on the relative phase between the radiation fields with frequencies ω_1 and ω_2 , while the energy spectra of the photoelectrons are independent of φ. On the contrary, when p is even, the energy spectra of the photoelectrons are affected by φ, while the angular distributions do not exhibit ones polar asymmetry. The figures show results of calculations pertaining a negative model ion simulating H^-. They have been carried out for $h\,\omega_L$ =0.002 eV, $h\,\omega_1$ =0.9 eV and at an intensity of the field of frequency ω_L of 10^6 W/cm^2. In Fig. 1 the differential cross section (DCS) for the process in which the electron absorbs 65 low-frequency photons and p is taken equal to 5 is shown. Fig.2 shows the energy electron spectra for p=6. Further results will be reported and commented on at the Conference.

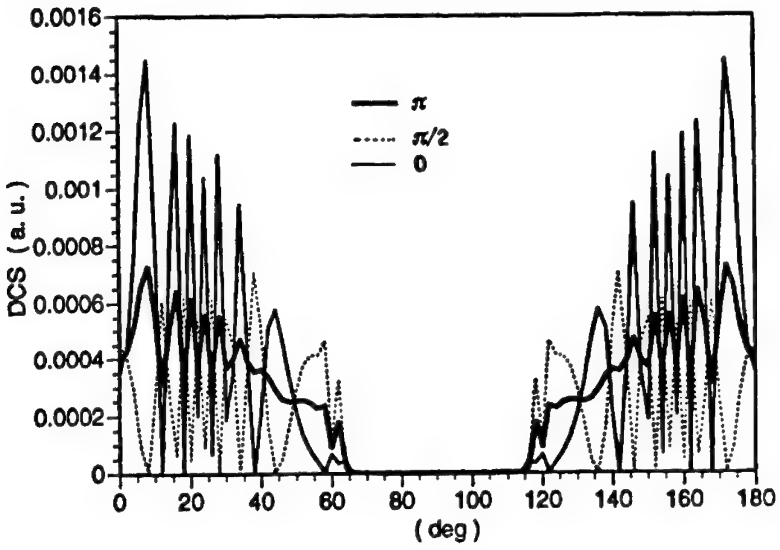

FIGURE 1

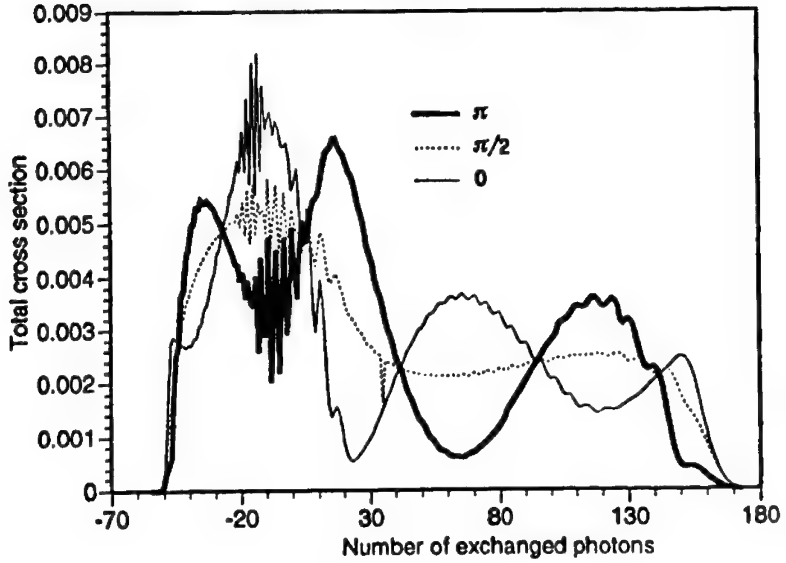

FIGURE 2

RESONANT STRUCTURE OF DOUBLY-CHARGED IONS CREATION AT NONLINEAR IONIZATION OF Sr AND Ba ATOMS IN INFRARED SPECTRAL RANGE

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For the first time the identification of resonant structure of doubly charged ions yield at nonlinear ionization of Sr and Ba atoms in IR spectral range was performed . It was discovered that the formation of these ions is the result of excitation and ionization of strongly perturbed by AC-Stark effect states of neutral atoms. These results show that in IR spectral range two-electron mechanism of doubly-charged ions formation is realized.

Our previous studies showed that the mechanism of doubly-charged ions A^{2+} formation at nonlinear ionization of alkaline-earth atoms in IR spectal range in unlike their ionization in visible spectral range is not step-wise [1,2]. These investigations show that the target for A^{2+} ions formation in IR spectral range are neutral atoms. However the resonant structure in dependencies of the yield of A^{2+} ions on frequency ω of laser radiation in IR spectal range is not unambigiously identified yet.

To elucidate this task we performed a number of

experimental investigations of a functions $N^{2+}(\omega)$ at ionization of Sr and Ba atoms in the radiation field of laser on colour centres (ω= 8300-9000 cm^{-1}) at different field strengths ($\mathcal{E}=10^6-5\cdot10^6$ V/cm). Laser pulse duration was $\tau=5\cdot10^{-8}$s.

We observed that measured functions $N^{2+}(\omega)$ have a clear resonant structure. The widths of maxima of this resonant structure $N^{2+}(\omega)$ are sufficiently larger than at ionization of Sr and Ba atoms in visible spectral range. It was also discovered that widths and amplitudes of these maxima are strongly dependent on $\mathcal{E}$. For maximal value of $\mathcal{E}$ realized in our experiment the widths of some resonant maxima reach 200 cm^{-1}.

The analysis showed that the observed resonant structue of these functions $N^{2+}(\omega)$ is caused by multiphoton excitation of perturbed in result of AC-Stark effect bound states of neutral Sr and Ba atoms. Note that the perturbation of Sr and Ba atoms in this case is very significant. In some cases shift of mentioned above states was $\Delta E \simeq 10^3 cm^{-1}$.

Thus, the result of these investigation together with investigations [1,2] show that the Sr^{2+} and Ba^{2+} ions formation in IR spectral range is result of direct ionization of neutral atoms.

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AC-STARK EFFECT AT MULTIPHOTON IONIZATION OF Sr AND Ba ATOMS IN STRONG FIELD OF INFRARED LASER RADIATION

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The influence of AC-Stark effect on multiphoton ionization of Sr and Ba atoms was studied. The new, unknown yet, character of manifestation of this effect was discovered. The conditions on which it's character of display depends were studied.

The experimental investigation of influence of perturbation on multiphoton ionization of Sr and Ba atoms using tunable IR radiation of laser on colour centres (ω = 8200-9100 cm^{-1}) was performed. The investigations were carried out at field strength $\mathcal{E} \leq 5 \cdot 10^6$ V/cm. The laser pulse duration was $\tau \approx 4 \cdot 10^{-8}$s.

The investigations showed that influence of used radiation on Sr and Ba atoms leads to strong AC-Stark effect. The character of manifestation of this effect at multiphoton ionization depends on correlation of laser radiation frequency (ω) with frequencies relevant to

multiphoton excitation of unperturbed states (ω_1) and one-photon transition from these states to other states (ω_2). So, in the case when $\omega=\omega_1\neq\omega_2$ correlation takes place the well known case of AC-Stark effect manifestation is realised. In this case the detunings and widths of resonant maxima in $N^+(\omega)$ function have a quadratic dependence on laser field strength $\mathcal{E}$.

The next case of AC-Stark effect manifestation is observed and studied by us for the first time. So, when $\omega=\omega_2\neq\omega_1$ correlation takes place at some values of $\mathcal{E}$ the induced maxima caused by excitation of strongly shifted states occur. The level shifts ΔE in this case are essentially larger than at ordinary manifestation of Stark-effect. In our conditions of experiment ΔE reaches the value 10^3 cm^{-1}.

In this case a multiphoton excitation of the same state manifests in a number of resonant maxima in $N^+(\omega)$ function. One of them occurs in the vicinity of frequency relevant to ordinary multiphoton excitation of this levels from ground state and other - in the vicinity of frequencies relevant to one-photon transition from this state to others. It was elucidated that a number of the later type of maxima depends on relation of different factors which describe the laser radiation, investigated atom and process of ionization.

DOUBLY-CHARGED STRONTIUM IONS FORMATION UNDER MULTIPHOTON ATOM IONIZATION IN 15000-16900 CM^{-1}

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The spectra of Sr^{+} and Sr^{2+} as functions of dye laser frequency were studied under fixed field strength. The majority of resonance maxima in the Sr^{2+} yield are unambigiously identified in ion spectrum by transitions as from ground as well as from first excited states. This fact indicates the realization of step-wise mechanism of doubly-charged ions formation. We alsoobserved a number of maxima which couldn't be identified by known resonant transitions neither in atomic spectrum nor in the spectrum of ion.

The process of multiphoton ionization of alkaline-earth atoms is intensively studied. The main question of interest is the mechanism of doubly-charged ions formation under multiphoton ioinization of these atoms. At present two possible mechanisms are considered: step-wise - when

doubly-charged ions are formed from singly-charged ions consiquently in two steps and so-called two-electron mechanism which suggests the simultaneous detachment of two electrons.

The formation of Sr^{2+} ions under multiphoton ionization by linearly polarized laser radiation in 15000-16900 cm^{-1} was studied. Note that in investigated spectral region the absorption of three or four photons is required for atom ionization and six photons - for ionization of ion. We measured the yields of singly- and doubly-charged ions as functions of frequency at fixed field strength $\mathcal{E}=2\cdot10^5$ V/cm. We observed a number of resonant maxima in both functions.

All resonant maxima in Sr^+ ions yield are unambigiously identified by allowed resonant transitions in the spectrum of Sr atom. The provided identification of resonant maxima in Sr^{2+} ions yield showed that almost a half of them are caused by resonant transitions in the spectrum of singly-charged ion. We observed resonance transitions not only from ground $5s^2S_{1/2}$ ionic state but from first excited $5p\ ^2P^0_{1/2}$ and $4d\ ^2D_{3/2}$ ionic states as well. The fact of manifestation in Sr^{2+} ions yield of resonance transitions in the spectrum of singly-charged ion unambigiously indicates the realization of step-wise mechanism of Sr^{2+} ions formation at these frequencies. Only one of observed maxima is identified in atomic spectrum and coincides on frequency with maximum in Sr^+ yield. This fact also could testify in favour of step-wise mechanism realization.

We had also observed five resonant maxima which was impossible to identify in both - atomic and ionic spectra by known allowed transitions. May be they are conditioned by excitation of unknown yet autoionizing states.

Time-Resolved Investigations on Optically Field Ionized Plasmas

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Abstract

The temporal evolution of optically field ionized helium and oxygen plasmas is studied. Different possibilities to control the plasma parameters for soft x-ray laser applications are demonstrated.

Time-Resolved Investigations on Optically Field Ionized Plasmas

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Summary

Results of time-resolved investigations of optically field ionized (OFI) helium and oxygen plasmas produced by focusing of 150 fs Ti:sapphire laser pulses into He and O_2 gas jets are reported. Linearly and circularly polarized pulses at 800 nm and at the second harmonic (400 nm) with energies of 100 mJ or 60 mJ are used.

In line emission of OFI plasmas we observe fast and slow components originating due to electron impact excitation and three-body recombination, respectively. Possibilities to manipulate these components on fs- and ns-time-scales are studied. In Fig. 1 the variation of the fast and slow HeII Balmer-α line emission components (λ = 164 nm) with the plasma length is shown. Nonlinear increase of the slow component, corresponding to a gain coefficient of $G = 8\ cm^{-1}$, is observed for the first time [1]. Analogous investigations have been performed with OFI oxygen plasmas, where soft x-ray amplification in OIII ions (λ = 37.4 nm) has been previously reported [2]. New results demonstrating the importance of some experimental arrangements will be presented.

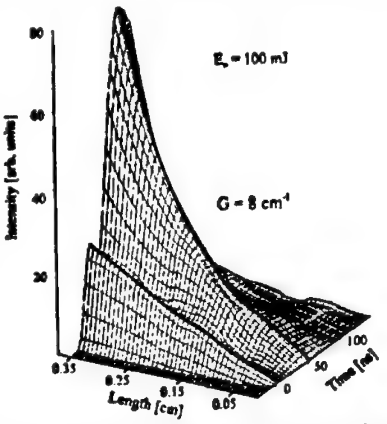

Fig. 1: Variation of the fast and slow HeII Balmer-α line emission components with the plasma length

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Time-frequency analysis of two-color high-harmonic generation

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Semiclassical three-step models [1] are able to explain most of the essential features of high-harmonic generation by a monochromatic driving field. Both theory and experiment have shown that high-harmonic generation by a two-color field displays a much richer phenomenology, owing to its increased parameter space which encompasses two intensities and, in case of the two driving fields having commensurate frequencies, the relative phase. In this paper we compare the predictions of the three-step model with those derived from a solution of the one-dimensional time-dependent Schrödinger equation (TDSE) [2]. In particular, we consider a $(\omega, 2\omega)$ two-color field with both components having equal field strengths and for various relative phases. In the framework of the TDSE, with the help of a wavelet or time-frequency analysis, we extract from the calculated dipole acceleration the times at which harmonic emission into a specified frequency range occurs. In the three-step model, these times are given by the return of the classical electronic orbit to the position of the ion. We obtain both the emission and the return times from the equations of motion of an electron in the presence of the driving field, either by an illustrative graphical method [3] or by numerical integration [4]. The cutoff-frequencies of the harmonic spectrum and, most remarkably, the return times calculated from the solutions of the time-dependent Schrödinger equation and from the semiclassical three-step model come out in striking agreement. This confirms the predictive power of the three-step model and its usefulness as an efficient guide through the parameter space towards the regions of interest. We also discuss characteristic manifestations in the harmonic spectrum of the transition from the multiphoton to the tunneling regime. The semiclassical three-step model ceases to work when one field component is very weak compared to the other.

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Momentum Transfer, Displacement and Stabilization

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Abstract

We consider one and three dimensional atomic models with attractive delta potentials in the presence of intense very shortly pulsed laser radiation. The problem of computing ionization probabilities is reduced to the problem of solving a Volterra equation of the second kind. We demonstrate that weak stabilization occurs when both the total classical momentum transfer and the total classical displacement vanish simultaneously. The effect is relatively stable towards small variations of the displacement, but more sensitive towards changes of the momentum transfer away from zero. There is no qualitative dependence on the dimensionality.

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Mapping, Inverted Harmonic Oscillator and Harmonic Oscillator with Imaginary Mass in High Order Harmonic Generation

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With intense field, the effects on atoms and molecules are ATI [1] and HOHG [2-3] (Above Threshold Ionization and High Order Harmonic Generation). A successful model for HOHG is essentially the two level system interacting with an external wave giving rise to the optical Bloch equation [4-6]. In order to fit the data, as well as intrinsically the model has 2 parameters. If we set the difference between the levels to zero, we reduce one of the parameters. Numerical simulation of HOHG demonstrate that for high intensities of the external wave there is no qualitative difference: both show the plateau structure, the abrupt fall-off etc. This degenerate system has been exactly treated long time ago [7] as a series expansion in the inverse power of the field-system coupling and also has been exactly solved recently [8].

The harmonics can be in that case written has a linear coupled map whose fixed point is studied[9]. Secondly for large harmonics the mapping can be transformed to a differential equation. Comparing with the equation of a harmonic oscillator one obtains either a harmonic oscillator with either an imaginary mass or one which is an inverted oscillator, depending on the point of view.

This has certain mathematical consequences and provides at the same time simplification for the treatment of HOHG when a single atom picture is valid. The mapping is reminiscent and useful for Lyapunov stability criteria for zonal adaptive-optics systems [10].

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PRODUCTION OF MULTICHARGED ATOMIC IONS FROM LASER-INDUCED MULTIPLE IONIZATION OF SMALL MOLECULES

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The production of C^{Z+}, N^{Z+} and O^{Z+} multicharged atomic ions up to $Z = 4$ is investigated using the laser-induced multiple ionization of small molecules in the gas phase in the 10^{15} - 10^{16} W/cm^2 laser intensity range. For molecules built with a single C, N or O atom and hydrogen atoms such as CH_4, NH_3 and H_2O, the $Z = 3$ and $Z = 4$ ion yields are systematically weaker than for molecules built with equivalent atoms such as N_2, CO, O_2, CO_2, N_2O using rigorously the same laser excitation conditions. In particular the C^{4+}, N^{4+} and O^{4+} ion production efficiency is more than one order of magnitude lower in the first case. In addition, no significant differences are found for the ion production efficiency between diatomic and linear triatomic molecular species built with the same atoms. This overall behavior remains the same at lower laser intensities in the 10^{14}-10^{15} W/cm^2 range for lower atomic ions charge states. The experimental results are interpreted in terms of the electronic density localization within each molecular species.

HIGH-ORDER HARMONICS GENERATION BY BICHROMATIC FIELD.

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Abstract: *A theory of high-order harmonic generation by bichromatic field is proposed. The theory is valid for exiting fields with comparable intensities. Calculations carried out in the frames of the theory show that adding a high-frequency exiting field significantly enhances harmonics conversion efficiency. The possibility of phase matching of harmonics under bichromatic excitation is being discussed.*

We have derived an analytical theory of HOHG by two exiting fields with frequencies ω_1 and ω_2 and ponderomotive potentials U_1 and U_2. The theory is valid if $U_1 / \hbar\omega_1 >> 1$ (the "strong" field is a low-frequency one) and either $U_2 / \hbar\omega_2 << 1$, $U_2 / \hbar\omega_1 << 1$ (the ponderomotive potential of the "weak" field is small) or (only for high-frequency harmonics) $\omega_2 << \omega_1$. The analytical formula for complex amplitudes of combined high-order harmonics is derived. The formula contains three-dimensional sum. The last can be reduced to the one-dimensional one in particular cases.

Results of simulation of combined high-order harmonics generated under bichromatic excitation ($I / \hbar\omega_1 = 10$ (I is ionisation potential), $\omega_2 = 3\omega_1$) are represented on Fig.1. The results are averaged over phase difference between the exiting fields. Adding the high-frequency exiting field with intensity ten times smaller, then the low-frequency exiting field intensity increases the plateau harmonics amplitudes by one+two orders of magnitude in agreement with experimental results [1]. The exiting fields amplitudes E_1, E_2 are chosen so, that $E_1 + E_2$ for curve 2 is equal to E_1 for curve 1; so the difference between monochromatic HOHG and bichromatic one is clear. The origin of the effect is going to be discussed.

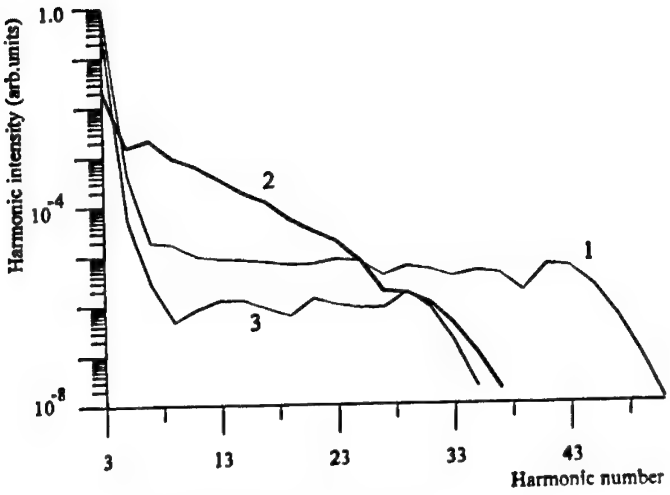

Fig. 1. Intensities of high-order harmonics generated by:
1 – monochromatic field with $U_1 / \hbar\omega_1 = 10$;
2 – bichromatic field with $U_1 / \hbar\omega_1 = 5.77$ and $U_2 / \hbar\omega_1 = 0.064$, $\omega_2 = 3\omega_1$;
3 – monochromatic field with $U_1 / \hbar\omega_1 = 5.77$.

The position of plateau cut-off slightly depends on a phase difference between the exiting fields (typically the difference is several harmonics). This dependence agrees with results of estimation in a semi-classical model.

The possibility of phase matching of harmonics under bichromatic excitation is also being discussed. It is shown that the phase matching can be provided under changing electron number density if one of the exiting frequencies significantly exceeds the other.

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Solid-state chirped-pulse amplification lasers for 10^{19}W/cm^2

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Two multi-terawatt solid-state laser systems developed in the Max-Born-Institute within the last few years are presented. They are a hybrid Ti:Sa-Nd:glass laser and an all Ti:Sa laser system. Both of them have 10 terawatt power.

The hybrid laser system has a Ti:Sa crystal based front end. The central wavelengths of the master oscillator and a regenerative amplifier used in the laser system (Spectra Physics) are shifted to 1054 nm to match the central wavelength of the phosphate Nd:glass medium used in the amplifiers. Starting with ~ 120 fs duration from the oscillator, the laser pulse is stretched to 1.5 ns and is amplified then in a successive amplification system. The input aperture of the laser is fully relayed to the output. The system has two output channels. One of the outcoming laser beams is recompressed in a grating compressor. The duration of the laser pulse at the output is limited by gain narrowing to ~ 500 fs. The laser delivers $E_{short} \leq 7$ J in the short-pulse recompressed beam and $E_{long} \leq 15$ J in the long-pulse beam. The recompressed beam is capable of achieving an intensity of 10^{19} W/cm^2 in the focal plane of an F/1.2 lens

In contrast to the glass system the all Ti:Sa laser is designed as a femtosecond CPA laser. It runs at a repetition rate of 10 Hz. The laser has a master oscillator with chirped mirrors (Stingl kit) which delivers 11 fs pulses with the wavelength centered at λ=780 nm. The laser pulses are stretched then to $\tau_{str} \approx 700$ fs and amplified in three multipass amplifiers. The second amplification stage delivers $E_2 \leq 15$ mJ pulses which can be optionally recompressed in an additional compressor to τ_{sm} ≈ 50 fs duration. The output power amplifier of the laser has a 20 mm Ti:Sa rod and is pumped at present by two YAG lasers with the total pump energy of 2.9 J. The laser delivers output energy of $E_{out} \leq 700$ mJ before recompression. To reduce the energy density on the gratings of the compressor the laser beam is recollimated to a diameter of ~ 70 mm before passing through of the compressor. The compressor is mounted in a vacuum chamber which is linked to interaction chambers with vacuum tubes. The outcoming laser beam has a duration of $\tau_{out} \leq$ 50 fs which corresponds to the laser power of $P \approx 10$ TW. Using an F/2 off-axis parabolic mirror we have measured an intensity exceeding $I \geq 10^{19}$ W/cm^2.

Both laser systems were used in laser-matter interaction experiments.

Two-electron atoms in strong ultra short laser pulses: Correlation effects

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We have developped a spectral method for solving the time-dependent Schrō dinger equation describing a two-active electron system exposed to strong laser pulses. Our method is based on the expansion of the total wavefunction into an overcomplete basis of products of single electron L^2 integrable functions. The overcomplete character of the basis leads to a better description of both electrons in particular for asymmetrically excited states. This in turn, gives rise to a drastic reduction of the size of the basis required.

In order to "probe" the electron-electron correlation, we used the so-called degree of correlation K which is defined as the trace of the reduced density matrix:

$$\rho(\vec{x}_1, \vec{x}_2) = \int \Psi(\vec{x}_1, \vec{x})\Psi(\vec{x}_2, \vec{x})d\vec{x}$$

where $\vec{x}_1$ and $\vec{x}_2$ represent the coordinates of both electrons and Ψ the total wave function [1,2].

This method is used to study correlation effects in the excitation and ionization of helium by an ultra short laser pulse. We also analyse the dynamics of two-electron wavepackets.

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OPTICAL TUNNELING AND FINITE MOTION OF AN ELECTRON

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Abstract –In a strong laser field a possibility of finite motion of an electron near the parent atom is established.

The dynamics of an atomic electron in a strong field of an optical pulse is investigated within the framework of the known "two step" semiclassical model for one-dimensional case. The second step classical equation of motion of an electron is analyzed in the approximation, which is similar to the Kramers-Henneberger approximation in a quantum consideration. It means that one accomplishes the passage to the oscillating system of coordinates and the replacement of the pulsating atomic potential by its averaged in time value in the equation of motion.

Apart from fast (at the radiation frequency) oscillations with a large (as compared to the atomic size) amplitude, an electron emerging from tunneling is involved in a slow motion in the field of the atomic residual. This motion is either finite or infinite, depending on the initial conditions of the appearance of an electron outside of the potential barrier. The fraction of electrons involved in finite motion is evaluated analytically for simple case when the tunneling probability of an electron per pulse is small as compared with unity.

The lower boundary of a high-frequency radiation range where the motion of an electron can be separated into fast and slow components is defined. This boundary depends on the strength of the radiation field and the binding energy of the electron. The corresponding restriction on the radiation frequency is sufficiently weak for the wide range of change of mentioned parameters, so that optical radiation certainly falls within the high-frequency range.

Influence of strong ionizing electromagnetic field on decay of the pair of autoionizing atomic states

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Abstract

It was shown that Raman transitions in strong ionizing electromagnetic field between two autoionizing states decaying to the same continua stabilize the channels of ionizing and autoionizing decay simultaneously.

Summary

Interference stabilization of autoionizing atomic states (AIS) in strong ionizing electromagnetic field (e.m.f.) was considered for the simplest model of Rydberg AIS-series. The model consists of two AIS and of two continua. Both AIS autoionize into the common lower continuum and they photoionize into the common upper continuum.

Quasienergy spectrum of the system was found and investigated. It was shown that in strong e.m.f. where ionizing width Γ_i is much more than the distance Δ between two AIS levels the width γ_- of one quasienergy state has a finite region of stabilization where γ_- is a decreasing function of e.m.f. intensity I. For Rydberg AI-states the minimum value of this width is proportional to $1/n^4$ (n>>1 is the principal quantum number of AIS) and in principle it may be less than the autoionizing width Γ_a of free AIS. At higher intensity γ_- grows again.

The finiteness of the stability region and the subsequent growth of γ_- are ensured if the parameter $\Phi \cdot \delta\Gamma_i \neq 0$, where Φ is nonpole term and $\delta\Gamma_i$ is the difference between the ionizing widths of two AIS.

Evolution of the probability amplitudes for initially populated AIS and the electron spectra in both continua were investigated. The absorption coefficient of probe e.m.f. was studied also. It was shown that all these functions reflect the quasienergy spectrum of the system. Particularly, stabilization of the width γ_- means that not only photoionization rate but the rate of autoionization are both the decreasing functions of intensity.

We see as the result that the Raman transitions through the ionizing channel in strong e.m.f. influence on the autoionizing channel caused by the other (configuration) interaction.

Model Calculations of High-Harmonic Generation in H_2^+

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Homonuclear molecular ions such as H_2^+ with their large transition dipole moments irradiated by intense laser fields reveal in their harmonic spectra both qualitatively and quantitatively novel features [1-4] if one allows for larger-than-equilibrium nuclear separations as they will occur in high vibrational states or during Coulomb explosion. An electron bound in such a two-center potential generates harmonic spectra that combine typical properties of atomic spectra (with their extended plateau and cutoff near $I_p + 3U_p$) on the one hand and two-level system spectra (with their cutoff proportional to the Rabi frequency) on the other. Moreover, harmonic emission due to the two-level mechanism is very intense.

We model such a homonuclear molecular ion by a two-center zero-range potential (ZRP).The one-center ZRP [5] yields a good description of atomic harmonic generation closely related to results obtained within the Lewenstein model. The two-center ZRP again allows for an almost analytical solution. In contrast to numerical solution of the time-dependent Schrödinger equation, arbitrary orientation between the molecular axis and the field and/or laser polarizations other than linear can be readily considered. The analytical expressions obtained and the associated explicit results lend themselves in a natural fashion to interpretation in terms of electronic trajectories in the context of the three-step model of Corkum and Kulander. The novel feature is that the electron set free in the continuum may travel from one center to the other before it recombines.

The figures exhibit examples of geometrical effects. Figure 1 illustrates the transition from orientation parallel to the driving field to perpendicular orientation. In the course of it the low-energy two-level part of the spectrum disappears. In Fig.2 the orientation of the molecular axis is perpendicular to the large component of the elliptically polarized field, and the polarization changes from linear to circular. The spectrum turns, respectively, from atomic to two-level type. The dipole phase (not shown) within the two-level part of the spectrum is locked and intensity independent. This has important consequences for the collective response of an ensemble of ions.

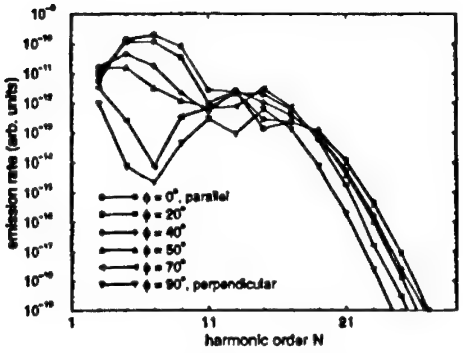

Figure 1: Parameters in a.u.: $\omega = 0.076, I_p = 0.65, U_p/\hbar\omega = 1.62$, nucl. sep. = 8

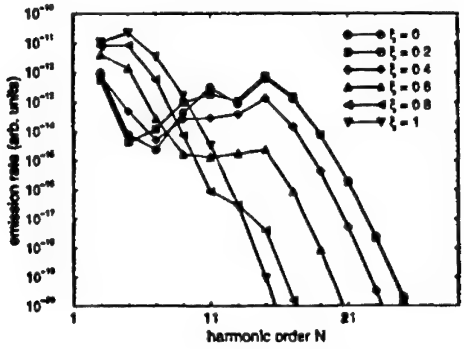

Figure 2: Same parameters as in Fig.1

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Coulomb Modification of Relativistic Spatial Distribution of Tunnel Photoelectrons in Superstrong Laser Field

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Influence of both relativistic effects and Coulomb electron-ion interaction on spatial distribution of the electrons born via tunnel ionization of atoms (ions) in superstrong laser field is investigated. Under certain conditions the distribution has a double-peak structure. This effect is sensitive to the ion charge and could be used for ionization control.

Laser radiation of relativistic intensity ($I \sim 10^{18}$ W/cm^2, $\lambda \sim 1$ μm) is now available making possible experimental investigations of relativistic features of above-threshold photoelectrons evolution (see, e.g., [1]). Theoretical background of these experiments does not take into account Coulomb interaction of quasi-free electron with its parent ion. However, there should be essential effects due to simultaneous influence of relativistic effects and Coulomb interaction on electron motion in the continuum. We have investigated the spatial distribution of above-threshold photoelectrons produced in tunnel ionization of multicharge ions. Relativistic effects (mass shift and magnetic component of laser field), electron-ion interaction and time-spatial inhomogeneity of laser radiation have been taken into account in the frame of unified approach [2].

Due to Coulomb interaction there is a distinction in evolution of "symmetric" electrons (electrons 1, 2 born at the moments $t_{1,2} = t_0 \mp \delta t$ that are symmetric about the phase t_0 of laser electric field maximum, see frame at Fig.). If Keldysh adiabatisity parameter $\gamma << 1$, this distinction is not essential, and "symmetric" electrons contribute to approximately the same point of θ–distribution (θ is an angle between electron drift velocity and pump wave vector). However, for $\gamma \leq 1$ due to increasing of Coulomb interaction, "symmetric" electrons could contribute to essentially different points θ_1 and θ_2. The difference $\Delta\theta = |\theta_1 - \theta_2|$ depends on laser intensity and ion charge. It also depends on the phase of ionization (maximum value of $\Delta\theta$ corresponds to ionization phase for which electrons return to the parent ion with a minimal kinetic energy).

Also, distinction in the evolution of "symmetric" electrons depends essentially on the pump pulse duration. In the long pulse photoelectrons escape interaction volume in transverse direction. Due to longitudinal drift photoelectrons pass by the parent ion at large distance. The trajectories of "symmetric" electrons is practically identical, and spatial distribution of electrons keeps a single-peak structure. Position of this peak is

determined by well-known formula $tg^2\theta = 2mc^2/E_d$ (E_d is an electron drift energy) and changes from $\theta = 90°$ to smaller θ with γ decrease. The width of this peak is formed by electrons born at different phase of ionization, and small distinction in the trajectories of "symmetric" electrons broadens this peak.

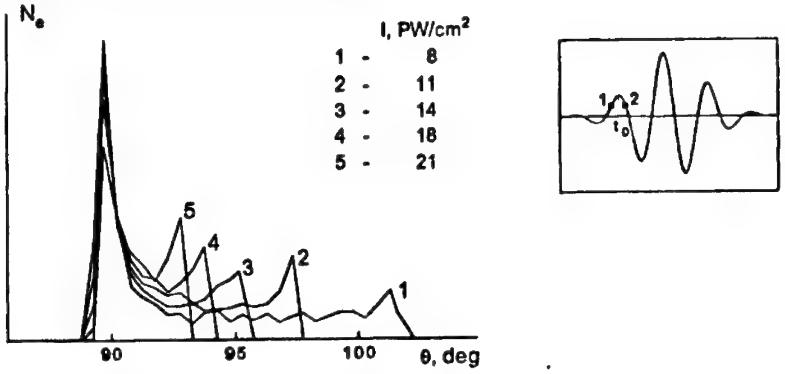

Fig. Electrons θ–distribution for tunnel ionization of Ar^{8+} ions by elliptically polarized ($\alpha = 0.04$) laser radiation with short pulse duration 100 fs, λ=1 μm and different peak intensity I.

For short pump pulse electron longitudinal motion is significantly reduced by gradient force on the trailing edge of the pulse: photoelectrons could pass by the parent ion at quite small distance and the distinction in evolution of "symmetric" electrons becomes more pronounced. In this case photoelectrons spatial distribution is concentrated near $\theta \sim 90°$. This forward peak does not change essentially with the increase of parameter γ. However, at $\gamma \leq 1$ there appears in the θ-distribution a number of backscattered electrons (electrons like 2) which form an additional (backward) peak (Fig.). Calculations show that difference in position of forward and backward peaks could reaches the value $\Delta\theta = 10°$-$15°$ and decreases with: (1) laser intensity growth (Fig.), (2) laser elliptisity growth and (3) ion charge decrease.

Finally, if simultaneously there are ions with different charge in interaction volume, electron spatial distribution could acquire a multi-peak structure that could be used for ions charge identification.

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Above Threshold Dissociation and Wave Packet Propagation.

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Above Threshold Dissociation has been defined long time ago [1], soon after the appearance of Above Threshold Ionization [2]. Since then no experience has clearly demonstrated ATD, which requires absorption of photons in the vibrational continuum, in contrast to electronic continuum, the time scale of the processes being entirely different, due to the relative mass of electrons vs nuclei. The coupling with the external field is thereby entirely different and has to be looked at in the Born-Oppenheimer framework. The ATD process needs not to be done with a large number of absorbed photons, as in ATI [2], and requires much lower intensities to be observed. But, even then, the intensity required will normally ionize a diatomic molecule, which is the simplest to consider. So we prefer to work with molecular ions, which can be either produced by a second laser, or by resorting to molecular ion beams.

We have calculated the probabilities of normal photodissociation and of the ATD process as a function of pulse length, frequency and intensity of a laser for the Na_2^+ molecular ion [3,4]. The potential energy curves of ground and several excited states of Na_2^+ were previously determined with good accuracy by model potential techniques [5]. The photodissociation process is simulated as wave packet propagation [6,7]. During the meeting, results will be presented and discussed, and further progress on this topic will allow a systematics for a set of diatomic molecular ions [8].

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Strong laser field effects in spectral lines of autoionizing atomic states*

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Abstract

In the resonance approximation and with adiabatic conditions a formula is obtained for the ionization cross section in a probe electromagnetic field in the vicinity of an autoionizing state (AIS) coupled with another AIS by a strong resonance field. The results of the calculations are in good qualitative agreement with the spectral dependence of the ion yield in the experiment with two-photon ionization of the Mg atom via the $3p^2\ ^1S$ AIS, strongly coupled with the $3p3d\ ^1P$ AIS by a laser field.

We derive an analytical expression for the photoionization cross section (PCS) in a probe electromagnetic field (EMF) in the vicinity of an AIS which is coupled to another AIS by a strong monochromatic (single-mode laser) field. We start from the resonance approximation previously applied to this problem [1, 2]. In addition, the adiabatic variation of the EMF amplitudes with respect to the life time of AIS is assumed. For the weak probe field and linear polarization, the system can be described in terms of two coupled quasi-levels. The solution gives the spectral dependencies of PCS in the form [3]

$$\sigma(\Omega,\omega,F)=\sigma_0(\Omega)\,\Im\,\frac{\begin{vmatrix} i & \gamma_1^a\rho(q-i) & -i(\gamma_2^{a'}\rho'+\gamma_2^{a-}\rho) \\ \gamma_1^a\rho(q-i) & \epsilon_1+i & \gamma_{12}(1-i/Q) \\ -i(\gamma_2^{a'}\rho'+\gamma_2^{a-}\rho) & \gamma_{12}(1-i/Q) & \epsilon_2+i \end{vmatrix}}{\begin{vmatrix} \epsilon_1+i & \gamma_{12}(1-i/Q) \\ \gamma_{12}(1-i/Q) & \epsilon_2+i \end{vmatrix}}, \qquad (1)$$

where Ω and ω are the probe and strong field frequencies; σ_0 is the direct (non-resonant) PCS of field-free atom; $\rho^2 = \sigma_a/\sigma_0$ is the PCS fraction of the part of continuum interacting with AIS; $\rho'^2 = 1 - \rho^2$; $\epsilon_n = 2(\Omega + (n-1)\omega - E_n)/\Gamma_n$ is the reduced resonance detuning for the quasi-levels E_1 and $E_2 - \omega$ with the total widths $\Gamma_n = \Gamma_n^a + \Gamma_n^{c+} + \Gamma_n^{c'+} + \Gamma_n^{c-} + \Gamma_n^{c'-}$; Γ_n^a, $\Gamma_n^{c,c'\pm}$ are the autoionization, strong field photo-absorption and induced photoemission partial widths with the corresponding branching ratios $\gamma_n^{a,c,c'\pm} = \Gamma_n^{a,c,c'\pm}/\Gamma_n$; $\gamma_{12} = 2\langle 1|z|2\rangle F/\sqrt{\Gamma_1\Gamma_2}$ is the AIS coupling parameter with a strong field intensity F; q is the Fano parameter [4] for probe field transition; and $Q = \gamma_{12}/(\gamma_1^a\gamma_2^{c-} + \gamma_2^a\gamma_1^{c+})$ is the analogues quantity for strong field transition between AIS. Note, that Q does not depend on F.

In the case when the bound-bound $1-2$ transition dominates over bound-free ones ($\gamma_1^a \approx 1$, $\gamma_2^c \ll 1$ and $Q \gg 1$), eq. (1) reduces to

$$\sigma(\Omega,\omega,F) = \sigma_0(\Omega)\Big[1 - \rho^2 + \rho^2\frac{(q+\epsilon_1)^2}{\epsilon_1^2+1+\gamma_{12}^2}\Big(1 + \frac{\gamma_{12}^2}{\epsilon_1^2+1}\frac{(q'+\epsilon_2')^2}{\epsilon_2'^2+1}\Big)\Big], \qquad (2)$$

where $\epsilon_2' = [\epsilon_2 - \epsilon_1\gamma_{12}^2/(\epsilon_1^2+1)]/[1+\gamma_{12}^2/(\epsilon_1^2+1)]$, $q' = (q\epsilon_1 - 1)/(q+\epsilon_1)$ are the Fano-type resonance parameters in the spectrum of strong field frequency with fixed probe frequency.

We applied eqs. (1), (2) to calculate the one-photon PCS of the He atom in the vicinity of the $2s2p\,^1P$ and $(23-)^1P$ AIS coupled with the $2p^2\,^1D$ and $2s3d\,^1D$ AIS correspondingly, by a strong EMF, and the two-photon PCS of the Mg atom in the vicinity of the $3p^2\,^1S$ AIS coupled to $3p3d\,^1P$ AIS. The spectral features of PCS for Mg atom are in agreement with the ion yield measurements and calculations in time-dependent density matrix approach [5].

We also will discuss the results for the two-photon strong field coupling of AIS via the common decay channel from the point of resonance trapping. This strong-coupling phenomenon investigated in open quantum systems leads to the formation of two different time scales in terms of the life times of the resonance states [6].

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Closed form for amplitudes of two-photon transitions between H-like states with arbitrary quantum numbers

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Abstract : A two-photon extension of the well-known Gordon formulas is given both for bound-bound and bound-free transitions. This result is sufficient for detailed analysis of two-photon transitions in H-like atoms including the Rydberg states and it completes the 30-year history of analytical calculations for two-photon processes in a Coulomb field.

The treatment of one-photon photoprocesses in H-atoms is based on the use of well-known Gordon formulas for the dipole radial matrix elements. The results are presented in terms of linear combinations of hypergeometric polynomials both for the bound-bound and for bound-free transitions. Using a new representation for radial part, $g_{l_g}(\mathcal{E}; r, r')$, of Coulomb Green function $G_\mathcal{E}$ [1], we derived the two-photon generalization of Gordon formulas. The radial parts, $M^{l_g}_{l',l}(\mathcal{E} = E_n \pm \omega)$, of the second-order matrix element (in velocity gauge; $\hat{\mathbf{p}} = -i\nabla$; $\mathbf{e}$ and $\mathbf{e}'$ are the polarization vectors of photons; the atomic units are used),

$$\mathcal{M} = \langle \psi_{n'l'm'} | (\mathbf{e}' \cdot \hat{\mathbf{p}}) G_\mathcal{E} (\mathbf{e} \cdot \hat{\mathbf{p}}) | \psi_{nlm} \rangle , \qquad (1)$$

are expressed in terms of *products* of hypergeometric polynomials by hypergeomeric functions ${}_2F_1$ for bound-bound transitions $|n, l > \rightarrow |n', l' >$ and by the Appel functions F_1 of two variables for bound-free transitions $|n, l > \rightarrow |n' = i/\sqrt{2E}, l' >$. All the known analytical results on the two-photon hydrogen calculations are the especial cases of our general result.

As an example we present here the explicit form of matrix element

$$M^{l+1}_{l'=l+2,l}(\mathcal{E}) = \left\langle R_{n'l+2}(r) \left| \left(\frac{d}{dr} - \frac{l+1}{r} \right) g_{l+1}(\mathcal{E}; r, r') \left(\frac{d}{dr'} - \frac{l}{r'} \right) \right| R_{nl}(r') \right\rangle , \qquad (2)$$

which is often most important among the radial matrix elements contributing the matrix element (1). $R_{nl}(r)$, $R_{nl+2}(r)$ are the radial wavefunctions. For the bound-free transitions the substitution $n' \rightarrow i/p$, $n'_r = n' - l' - 1 \rightarrow i/p - l' - 1$, where $p = \sqrt{2E}$, should be made in the results presented below and the re-normalization factor

$$- i^{l'} \left| \Gamma(l' + 1 - i/p) \right| / p^{l'/2} \left[2\pi (i/p - l')_{2l'+1} \right]^{1/2}$$

should be added in the right-hand side of Eq. (3).

The techique developed in [1] allows to write the matrix element (3) as follows:

$$M^{l+1}_{l+2,l}(\mathcal{E}) = 4\nu^3(4\nu\sqrt{n'n})^{2l}\frac{[(n'_r-1)_{2l+3}(n_r+1)_{2l+1}]^{1/2}}{[(n+\nu)(n'+\nu)]^{2l+2}}\{n_r(n_r-1)\Big(g^{l+1}_{n'_r,n_r-2}(n',n)$$

$$-g^{l+1}_{n'_r-2,n_r-2}(n',n)\Big) + (n+l+1)(n+l+2)\Big(g^{l+1}_{n'_r-2,n_r}(n',n) - g^{l+1}_{n'_r,n_r}(n',n)\Big)\}. \quad (3)$$

Here

$$g^l_{k',k}(n',n) = f(n',n)\sum_{p=0}^{k} C^k_p(-z)^p {}_2\mathrm{F}_1(-k+p, l+1-\nu+p, 2l+2+p, z)\Phi_p(y,y'),$$

$$f(n',n) = \left(\frac{n-\nu}{n+\nu}\right)^k\left(\frac{n'-\nu}{n'+\nu}\right)^{k'}, \qquad \nu = (-2(\mathcal{E}+i0))^{-1/2},$$

$$\Phi_{p=0} = \frac{1}{(2l+1)!(l+1-\nu)}\mathrm{F}_1(l+1-\nu, -k', k'+2l+2, l+2-\nu; y, y'),$$

$$\Phi_{p>0} = -\frac{(l+2+\nu-p)_{p-1}(y-1)^{k'}}{(p+2l+1)!(y'-1)^{k'+2l+2}}\cdot$$

$$\mathrm{F}_1(-p+1, -k', k'+2l+2, l+2+4-p; 1/(1-y), 1/(1-y')),$$

$$z = -\frac{4n\nu}{(n-\nu)^2}, \qquad z' = -\frac{4n'\nu}{(n'-\nu)^2}, \qquad y = \sqrt{\frac{1-z'}{1-z}}, \qquad y' = \frac{1}{\sqrt{(1-z)(1-z')}}.$$

C^k_p is the binomial coefficient. The above result for $g^l_{k',k}$ is valid at $n'_r \geq n_r + 2$. $n_r = n - l - 1$ and $n'_r = n' - l - 3$ are the radial quantum numbers of initial and final states.

It is important that the Appell function in $\Phi_{p>0}$ is a polynomial in both arguments. Therefore, $g^l_{k',k}(n',n)$ includes two essentially different groups of terms: The terms with $p > 0$ reduce to products of hypergeometric polynomials of one variable, in the ${}_2F_1$ function, and of two variables, in the F_1 function. The term with $p = 0$ involves the linear combination of $(k'+1)$ hypergeometric functions for bound-bound transitions and the Appel function for the bound-free case. The radial matrix elements with other values l' and l_g have the structure similar to Eq. (3).

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Multiphoton detachment and harmonic generation in the presence of a static electric field

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Nonperturbative rates of harmonic generation and of multiphoton detachment in the presence of a static electric field have been obtained for a one-electron model of the negative hydrogen ion, using the Sturmian-Floquet method. The addition of the static field leads to a strong production of even harmonics. The harmonic generation rates and the photodetachment rate oscillate when the strength of the static electric field increases, with a clear trend towards an overall *decrease* in the rate of emission of odd harmonics. The latter effect is consistent with the behaviour of the harmonic generation rates for a coherent superposition of an incident field and its third harmonic. Results for atomic hydrogen are also presented.

X-ray-atom scattering in the presence of a laser field

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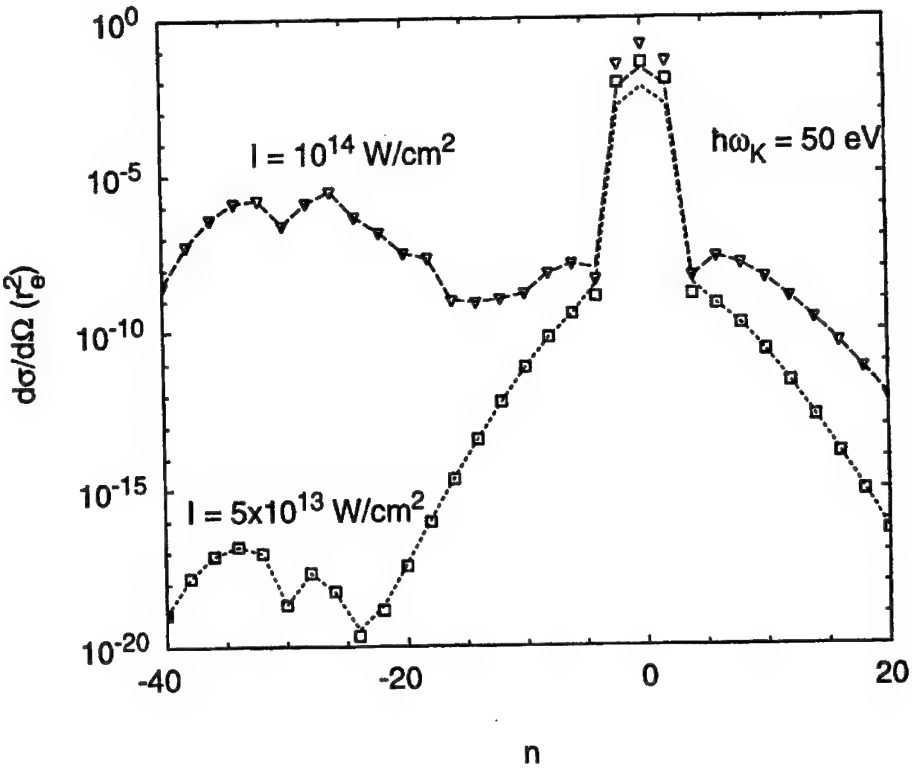
Abstract. We consider x-ray-hydrogen atom scattering in the presence of a monochromatic linearly polarized laser field. The S-matrix of this process is presented and an expression for the differential cross-section (DCS) is derived. We show that the time-dependent WBKapproximation can be applied to the present problem. The presented numerical results for the DCS as a function of the number n of photons exchanged with the laser field show a characteristic behaviour. The number n can only be even. For $n = 0, \pm 2$ we have pronounced maxima in the DCS, followed by sharp minima at $n = \pm 4$. After that, we have a plateau which is different for negative and positive values of n. The plateau for negative values of n is much more extended than for the positive ones. The structure of the plateau and the positions of the minima and maxima of the DCS do not depend on the laser field intensity, while the height of the plateaus strongly depend on it. We also analyze the dependence of the matrix elements of the x-ray spectra on the incident x-ray photon energies by using both, the saddle-point method and the numerical evaluation and we show that the shape and position of the plateau is determined by the simple relation: $n\hbar\omega = I_0 - \hbar\omega_K$. This condition connects the number of absorbed or emitted laser field photons n, the laser field photon energy $\hbar\omega$, the atomic ionization potential I_0, and the energy of the incident x-ray photon $\hbar\omega_K$.


10^0
10^{-5}
10^{-10}
10^{-15}
10^{-20}
$d\sigma/d\Omega\ (r_e^2)$
$I = 10^{14}$ W/cm^2
$I = 5x10^{13}$ W/cm^2
$\hbar\omega_K = 50$ eV
-40
-20
0
20
n

GENERATION OF A SINGLE ATTOSECOND SOFT X-RAY PULSE

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Abstract: *We are discussing new scheme for obtaining a single soft X-ray pulse by high-order harmonics generation in a gas layer using two circularly polarized in opposite directions laser pulses with the same frequency shifted in time relatively to each other (providing the field with modulated degree of ellipticity) . The HOHG takes place in converging beam. Numerical simulation using 10-cicle pulses shows that harmonics with different numbers are focused at different distances from the target. On the axis of the beam single attosecond soft X-ray pulse is formed with the carrying frequency depending on the distance.*

The possibility of attosecond pulses obtaining seems to be one of the most impressive application of HOHG. High-order harmonics generated in a monochromatic field of a long laser pulse can form a train of attosecond pulses [1,2]. A *single* attosecond pulse can be generated using either very short exiting pulse or exiting field with a time-modulated degree of ellipticity [3] (because the HOHG efficiency is very sensitive to the degree of ellipticity of the exiting field).

It was proposed [3] to use two exiting fields with slightly different frequencies to obtain a field with modulated degree of ellipticity. Such field was used in calculations [1]. We suggest a new method to modulate degree of ellipticity of exiting field using pulses with the same frequency. It is based on using two circularly polarized (in opposite directions) pulses. The pulses are shifted in time relatively to each other. The summarized field of the pulses can be written as:

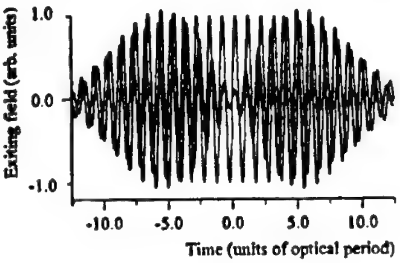

Fig 1. Exiting field. Thick curve – y-component, thin curve – x-component.

$$\bar{E}(t) = \bar{n}_x \cdot [E_0(t - \frac{nT}{2}) + E_0(t + \frac{nT}{2})] + \bar{n}_y \cdot [E_0(t - \frac{nT}{2} - \frac{T}{4}) + E_0(t + \frac{nT}{2} + \frac{T}{4})] \quad (1)$$

where $E_0(t) = E_0 f(t) \cdot \cos(\omega t)$, ($E_0$ and $f(t)$ are amplitude and envelope of a pulse). The number n always can be made integer by turning coordinate axes. The projections of the field on the axis is shown on Fig.1.

For calculating the generated field we use the formulae:

$$E_1(\bar{R},t) = -\frac{1}{c^2}\int \frac{1}{|\bar{R}-\bar{r}|}\frac{\partial}{\partial t} j^{nl}(\bar{r}, t - \frac{|\bar{R}-\bar{r}|}{c}) d^3r \quad (2)$$

where j^{nl} is the current density induced by the laser field. The method of calculation of the value of $\partial j^{nl}/\partial t$ is described in [4].

It occurs that in far zone diffraction provides spectral filtering [2]. Low harmonics strongly diverge due to large wave lengths; very high harmonics strongly diverge because they are generated only near the axis of the laser beam . The harmonics with intermediate numbers mainly survive and form attosecond pulses at the axis. Its structure changes with distance and depends on the waist diameter and wave front radius of laser beam; being generated in converging beam , any harmonic can be focused at the distance, depending on its number.

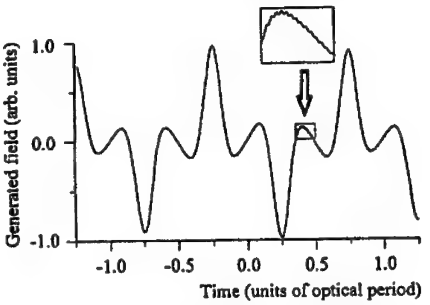

Fig 2. Field calculated by the formulae (2) at the distance from the waist about 2.5 confocal parameters.

The results represented on Fig. 2, 3 were obtained under ionization energy $I = 10\hbar\omega$, ponderomotive potential at the beam axes $U = 20\hbar\omega$, placing thin target in converging gaussian beam at the distance from the waist about one confocal parameter.

The field (2) in the far zone is shown on Fig.2. High harmonics are intense enough to be distinguished against a background of the lowest ones. Square of this field after suppression of the low-frequency part is shown on Fig.3. It contains only three peaks of soft X-rays light. The central peak is four times more intensive than others. The ratio can be increased using shorter exiting pulses or larger time shift between them.

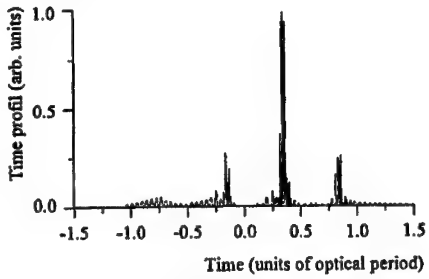

Fig.3. Square of the field shown in Fig. 2 after suppression of low-frequency part (up to 7-th harmonic).

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A program for time-independent calculations of multiphoton processes in one-electron atomic systems

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A program to be distributed through the Computer Physics Communications Library is presented. It calculates quasienergy spectra of one-electron atoms or ions undergoing multiphoton ionization in an intense two-colour field or ionization in a strong static electric field. The electron is initially bound by a single Coulomb potential or by a superposition of a short range potential and a Coulomb potential. Besides quasienergies, the program can obtain rates of photoionization in specific ATI channels and angular distributions of photoelectrons, in the approximation where the atom is represented by a single dressed state. The calculation can be perturbative or nonperturbative. The Floquet equations are solved on a basis of spherical harmonics and complex Sturmian functions.

Direct shaping and amplifing of high-intense single attosecond pulses from high-intense femtosecond optical pulses in inert gases.

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The possibility of a direct shaping and amplifing of high-intense single attosecond pulses from femtosecond optical pulses under stimulated electronic Raman self-scattering (SERSS), is invcstigated by numerical simulation. It is for 2π and 4π pulses at predicted previously self-induced transparency (SIT) in SERSS that the high-efficient conversion and amplification is found.

At the present time, as far as know to us, all proposed models to generate attosecond pulses, are associated with generating a train of ones having a peak pulse intensities no more than, and more often, much below than the intensity of driving pulse (see for ex. [1] and Refs. cited in these ones). The possibility to generate single attosecond pulses by 2π pulses at predicted previously self-induced transparency (SIT) in stimulated electronic Raman self-scattering (SERSS) [2] had been predicted theoretically [3].

Dynamics of intense laser field in medium, in SERSS [2,3] (laser pulse (LP) with duration τ and frequency ω, which satisfies the conditions $\tau^{-1} > \Omega$, $\omega >> \Omega$, where Ω is the frequency of Raman transition), is investigated.

The LP which is propagating along the z direction, having the intensity defined by the condition $\psi(\tau, z) = 2\pi\ (\psi(t, z) = \mid \alpha_{12} \mid / \hbar \cdot \int_{-\infty}^{t} E^2(t', z)dt'$, E is the electric field of the pulse, $\mid \alpha_{12} \mid$ is the matrix element of polarizability), can pass trough media on the distance $\sim 1/\beta$ do not experiencing absorption due to SIT at SERSS [2,3], were $\beta = 2\pi N \mid w_0 \mid\mid \alpha_{12} \mid v\Omega/c^2$, N is the particle density, w_0 is the initial difference of level populations, v is the pulse velocity determined by the linear contribution to the medium's polarization. The SIT at SERSS is two-quantum process and the LP, conserving energy, itself is not stationary in shape and spectrum [2,3]. There are possibilities in the regime to generate spectral supercontinuum [2] and single attosecond pulse by fs 2π-pulse [3]. In this case the trailing edge of the LP is enriched with high-frequency components into which the energy of the leading front is transferred, and the LP become compressed.

We have carried out the computer simulation of propagation of 2π and 4π-pulse in case SIT at SERSS and found out that exist the possibility of the high efficient generation of high-intense attosecond pulses. The decomposition 4π pulse at the SIT in SERSS into 2 propagating 2π pulses takes place as for a single quantum, double quantum and ordinary Raman quantum transition SIT, but in contrast to these SITs the 2π pulses in SERSS are nonstationary ones both shape and spectrum. In this case the initial LP, τ_0 =8 fs (FWHM) at the wavelength 800 nm) is transformed in two LP generating spectral supercontinuum, as high-frequency components of the first LP are amplified and amplitude of the second LP is decreasing in the process of propagating in medium. The first LP is transformed in the LP of width τ =0.3 fs (half-cycle of electromagnetic field) having energy about 10% of the energy of the initial LP by advancing to $\beta \cdot z = 1$ in case SIT at SERSS.

For example, there are two-photon excitation and the stimulated Raman process having the two-photon Rabi frequency $\simeq 10 \cdot I(W/cm^2)$ and effective cross section $\sigma_{eff}(cm^2) \simeq 10^{-27} \cdot I(W/cm^2)$ in Xe atoms [4], and be have the $\psi(\tau, 0) \simeq 4\pi$ and $\beta = \sigma_{eff} \cdot N \simeq 10^1 cm^{-1}$ for τ = 8 fs, $I = 1.6 \cdot 10^{14} W/cm^2$, $N = 10^{17} cm^{-3}$. In our case the best examples of the electronic SERSS may be realized at transitions between fine structure $^2P_{3/2} - {}^2P_{1/2}$ levels of F,Cl,Br,I atoms or

Ne^+, Ar^+, Kr^+, Xe^+ ions, because the other terms of these atoms and ions are far from the above terms.

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The (linear and) non-linear susceptibilities of acetylene relevant for high order harmonic generation

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High order harmonic generation appears to be a well understood phonomena. It is generated for practically all atoms and molecules and as the intensities of lasers utilized continue to increase, the number of harmonics have gone so high as to produce photons of $\approx$ 400 eV. It is also interesting to note that even complicated molecules like acetylene generate high order harmonics and sometimes they have been useful to measure quantities of fundamental physics rather than concentrate on breaking records [1].

There are many theories of HOHG: classical, semiclassical, quantal with (α) single atom picture and (β) the effect of the medium composed of the atoms or molecules. Often only the first approach is enough, but in many cases (β) is necessary, the term phase matching describing the situation well.

In this communication, we concentrate on a difficult species – acetylene – as the medium. We had calculated properties that were relevant both for the rare gases [2] and acetylene [3]. Here we report $\chi^{(3)}_{THG}(-3\omega;\omega,\omega,\omega)$ as a function of frequency ω. For large intensity, this is of fundamental interest for studying the generation of harmonics in relatively dense medium for acetylene. The results will be displayed during the conference.

The calculations have been done for both the frequency dependent electric dipole polarizability $\alpha(-\omega;\omega)$ and Third Hamonic Generation second hyperpolarizability

$\chi^{(3)}(-3\omega;\omega,\omega,\omega)$ af acetylene in the Multiconfigurational SCF (MCSCF) Linear and Cubic Response approach, involving a large configuration space (> million determinants) and a correlation consistent basis set of Triple-Zeta quality. For $\alpha(-\omega;\omega)$ the present results improve those obtained with the same technique ten years ago [3].

These results will serve as the input for future experiments and most likely will be useful when the harmonics are not extremely high such as 500 or so. In that case, simplified models will be needed and one of that is shown in another poster, whose preliminary version is already in the literature [4].

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Efficient Hard X-ray Production from Femtosecond Plasma Induced in Volume-Structured Solids

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We discuss hot ions, suprathermal electrons and hard x-ray production in fractal low density materials such as porous semiconductors, metals and oxides.

Fractal volume-structured solids (VSS) with density as low as 0.1 of the bulk ones reveal very specific properties under irradiation by femtosecond laser pulse with intensity in excess of 10^{15} W/cm^2 [1,2]. Plasma formed possesses extremely high ion temperature of 10-100 keV, and it is proved to be very efficient source of hot electrons and hard x-rays. Porous semiconductors and oxides here could not only serve as VSS target itself but could be used to create VSS made of other materials (metals, etc.).

In this paper we report on our recent progress in both experimental and theoretical investigation of interaction of superintense femtosecond laser pulses with VSM materials.

In performing experiments on femtosecond laser-plasma interaction we used femtosecond laser system described elsewhere [1], which provides intensity in excess of 10^{16} W/cm^2 with intensity contrast ratio better than 10^5.

Two-channel hard X-ray detection scheme allows to monitor x-ray flux above 5 keV simultaneously with measurements of hard x-ray yield in different quanta energies with the help of metal foil filters. Each channel consists of 100 μm Be output window (0.5 transparency for 5 keV quanta energy), additional foil filters (Al, Ta, Cu), and NaI(Tl) crystal along with photomultiplier tube. For 0.5 mm Cu foil only quanta with energy above 60 keV were detectable. Specially prepared porous semiconductor and oxide samples as well metal VSS were used in experiments.

Computer simulation neglecting hot electron production predicted mean electron temperature of 0.4 keV for bulk Si target and intensity of 10^{16} W/cm^2.

Quantitative analysis of hard x-ray data obtained for different laser intensities and x-ray filters showed that electron temperature of 2-3 keV should be superimposed to fit the data for solid targets, and as high as 5-7 keV for VSM ones.

In this paper we will also address theoretical model, describing interaction of superintense laser pulses with VSM.

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Two–electron atoms in short intense laser pulses

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Abstract: We present accurate *ab initio* calculations of double excitation, ionization, and harmonic generation in He and H^- by short ($\lesssim 40fs$) strong laser pulses. Intensities reach up to $10^{15}W/cm^2$ at laser wave length $\geq 248\,nm$ in He and $10^{12}W/cm^2$ at $1350\,nm$ in H^-. The observables are determined with accuracies of $\lesssim 10\%$.

The field strengths of laser pulses that are routinely used in experiments approach and in some cases surpass the atomic field strength. Such high fields may be obtained with pulses whose duration is less than 100 femtoseconds. A theoretical interpretation of experiments under such conditions requires a non–perturbative and non–stationary description of the laser–atom interaction. The interest in going beyond the picture of a single active electron (SAE) is twofold: first, to provide an independent check of the SAE model, and second, to be able to describe genuine two–electron phenomena like double excitation or (non–sequential) double ionization.

We solve the complete time–dependent Schrödinger equation of a two–electron atom in the presence of a laser pulse. For our calculations we use an expansion in explicitly correlated two–electron basis functions combined with complex scaling. The explicitly correlated basis gives a very accurate description of atomic structure including doubly excited states with a relatively short expansion. Complex scaling provides a computationally efficient method of dealing with the continuous spectrum. We will argue and provide numerical evidence that it is equivalent to the use of strictly outgoing wave boundary conditions. The penalty of the method is the loss of a direct physical interpretation of the continuous spectrum of the complex scaled operator.

Accurate atomic structure: The expansion in explicitly correlated Hylleraas–like basis functions of the form

$$|L, l_1, k, m, n\rangle = G_{Ll_1}(\vec{r}_1, \vec{r}_2) r_1^k r_2^m r_{12}^n e^{-\alpha_s r_1 - \beta_s r_2} \tag{1}$$

is highly efficient in describing the structure of two–electron atoms. For each angular momentum L a total number of $\sim$ 300 functions simultaneously reproduces the

four lowest bound states with accuracy $\approx 10^{-7} a.u.$ and the most important doubly excited state energies with accuracies of $\approx 10^{-4} a.u.$. A maximum of $L = 7$ angular momenta is used in the calculation.

Double excitation: In He we find far off-resonant transitions that are due the short pulse duration. Otherwise the dominant process is resonant population of the various doubly excited states. A clear signature of the process should be identifiable in the higher ATI peaks.

Ionization: At the experimentally popular laser wave length of $248 nm$ we calculated the ionization yield by a laser pulse of 40 optical cycles at intensities up to $10^{15} W/cm^2$. By variations of the basis parameters and convergence studies we determine the accuracy of our calculations to $\lesssim 10\%$. The comparison with a previous calculation in the table shows quantitative disagreement by about 50%.

$I\,(W/cm^2)$	present	Ref. [2]
2×10^{14}	7.06×10^{-3}	8.13×10^{-3}
2.5×10^{14}	0.00105	0.00148
5×10^{14}	0.043	0.069
1×10^{15}	0.18	0.33

In electron detachment from H^- we confirm the effect of channel closure by the AC-stark shift at a laser frequency of $0.03 a.u.$ predicted by a Floquet calculation [3]. For pulse durations of $\gtrsim 16$ optical cycles the solution of the TDSE is in good agreement with the Floquet results averaged over the pulse envelope.

Harmonic generation: The dipole expectation values $\vec{d}(t)$ are sensitive to the wave function at larger distances. To obtain accurate results we had to add extra basis functions with smaller exponents to cover a longer range in r_1 and r_2. We were able to obtain satisfactory accuracies of $\lesssim 10\%$ up to the 5th harmonic for frequencies in the range 0.34 to $0.42 a.u.$ and intensity $I = 2 \times 10^{14} W/cm^2$. The frequencies include a strong resonance with the lowest excited S-state that greatly enhances harmonic generation and leads to the dominance of the 3rd harmonic over the 1st.

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Hot Electrons in the Tunneling Ionization of Atoms

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Summary

A compact generalization of Landau-Dykhne approach [1] is derived for the ionization rate of atoms by low-frequency laser radiation that includes rescattering analytically. It is used for calculations of energy spectra of cold and hot electrons for tunneling ionization of atoms at high intensity. Most of the essential features of recent measurements and numerical derivations [2,3] are reproduced, that is, the onset, the extent, and the relative height of the plateau, which makes up the major part of the observed energy spectrum. Analytical expressions for quantum tunneling interferences in energy spectra are given which are in agreement with derivations of Ref. [4].. Detailed description of results of this summary is published now [5]. Everywhere the atomic system of units is used: $\hbar = m = e = 1$.

The energy and angular spectrum of *cold* (direct) electrons is given by expression:

$$dw(p) = Cp\cos^2\left(\frac{pE_0}{F} + \frac{p^3}{6F}\right)\exp\left\{-\frac{(2E_0)^{3/2}}{3F}\left[1+\left(\frac{p\omega}{F}\right)^2\right] - \frac{\sqrt{2E_0}}{F}p_\perp^2\right\}d\Omega. \quad (1)$$

Here p is the kinetic longitudinal momentum of the ejected electron, E_0 is the ionization potential of the considered atom, F, ω are the field strength and field frequency of laser radiation, respectively. $p_\perp$ is the transerse momentum of the ejected electron. The constant C does not depend on p.

Pre-exponential cosine term in Eq. (1) presents analytical form of quantum tunneling interference for direct electrons found in Refs. [3, 4] produced by two classical turning points in upper plane of complex time on one laser cycle.

The energy spectrum of *hot* (after rescattering) electrons is given by the same simple expression, but with the substitution (in the sakes of simplicity we consider the case of backscattering only):

$$p \to \tilde{p} = p + \frac{2F}{\omega} \cos(\omega t_0 + \varphi) \ll p. \qquad (2)$$

Here φ is the phase of the laser field, and $t_0 = t_0(p, \varphi)$ is the time for returning of the electron. The small value of the effective electron longitudinal momentum $\tilde{p}$ produces more fairly broader tops in energy spectrum compared to the case of direct electrons.

Besides of this, the energy spectrum of hot electrons contains small factor since only small part of electrons returns back to the atomic core. The most of the electrons acquire the transverse momentum $p_\perp$ and avoid the collision with the atomic core. In the assumption that Bohr radius of atomic core restricts the amount of electrons which scatter on the core, we obtain the estimate for solid angle of returning electrons:

$$C = \frac{d\Omega}{4\pi} \sim \frac{\omega^4}{F^2} \ll 1. \qquad (3)$$

This is the small additional factor in the energy spectrum of hot electrons which gives small relative height of the plateau.

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Harmonic Generation and Propagation: Double Driving Laser Pulse

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We compare the harmonic yield from experiment and theory for a double pulse driving laser field. The driving pulse in the experiment is obtained by splitting a 40 fsec Ti:Sa laser pulse and superposing the two pulses with a delay controlled to about $\lambda/20$. The calculation uses a delta-atom model rate [1] together with a 3D propagation code [2] which includes ionization and fundamental beam propagation.

Pronounced interference structure is visible in the harmonic yield as a function of the delay between the pulses on the scale of the laser cycle, due to interference between the two pulses. As the delay becomes comparable to the pulse duration, the interference pattern exhibits an envelope which can be used as a high-order autocorrelation function of the harmonics as they are created inside the medium.

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High-Order Harmonic Generation: Enhanced efficiency with sub 50 fs Laser Pulses

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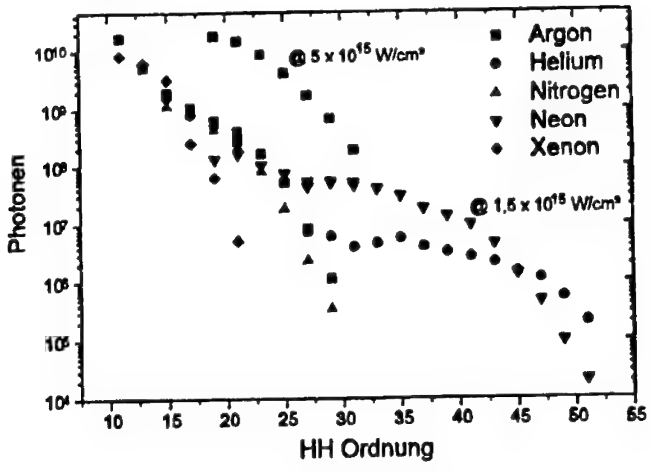
We present results of experiments studying the influence of laser pulses shorter than 50 fs on high-order harmonic generation. Using different rare gases we report photon numbers of more than 10^{10} for the 19th and 21st harmonic of a titanium:sapphire laser radiation at 795 nm central wavelength. These high photon numbers are produced with little energy per titanium:sapphire laser pulse (3 mJ). We therefore have a high conversion efficiency of laser energy in high harmonic energy of more than 10^{-5} per harmonic.



Classical and quantum theory of orientation and dissociation of diatomic molecules and their ions in a strong laser field

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Summary

Vibration, rotation and dissociation of the simple diatomic molecular Cl_2^+ and H_2^+ ions perturbed by a strong laser pulse with linear polarization are considered in the frames of classical mechanics. It is found that the duration of the laser pulse influences the rotation of the molecular axis and the vibration of the internuclear separation. The molecular axis of the heavy molecular ion Cl_2^+ is strongly rotated after the end of the ultrashort laser pulse, while the alignment of the H_2^+–ion axis occurs in the rise of the long laser pulse due to quick dissociation. Angular distributions of protons in dissociation of H_2^+–ion are calculated.

Dissociation of benzene molecule in a strong low-frequency linearly polarized laser field is considered theoretically under the conditions of recent experiments. Analogy with the dissociation of diatomic molecules has been found. The probability for dissociation of benzene molecular ion into the equal fragments after the single ionization of a neutral benzene molecule has been derived as a function of time. It is shown that three-photon dissociative process is realized in experiments.

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PROOF OF REALIZATION OF TWO-ELECTRON MECHANISM OF Ba^{2+} IONS FORMATION AT MULTIPHOTON IONIZATION OF ATOMS IN 9390-9460 cm^{-1} SPECTRAL REGION

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Our observations consist of spectra of Ba^{+} and Ba^{2+} as function of Nd-glass laser frequency and intensity. The results of experiments unambiguously prove the realization of two-electron mechanism (direct double ionization) of Ba^{2+} ions formation.

Beginning with first experiments where the effect of double-charged ions formation was discovered [1] the search for manifestation of two-electron mechanism of doubly-charged ions formation is intensively carried out. Integrated study including investigations of yields of singly- and doubly-charged ions (N^{+}, N^{2+}) as functions of frequency (ω) and intensity (F) of laser radiation was performed to investigate the mechanism of doubly-charged ions formation. In $N^{+}(\omega)$ dependence in the yield of Ba^{+} ions there are maxima at the frequencies 9405 and 9462 cm^{-1} which are caused by five-photon excitation of autoionizing state and by four-photon excitation of $5d6d\ ^{1}D_{2}$ state, correspondingly.

While studing $N^{2+}(\omega)$ function in the yield of Ba^{2+} ions in 9390-9500 cm^{-1} spectral region one can see one wide maximum ($\simeq$20 cm^{-1}) at 9405 cm^{-1}. Coincidence of frequencies at which resonance maxima in both $N^{+}(\omega)$ and $N^{2+}(\omega)$ functions appear couldn't be an unambigious conclusion about mechanism

of doubly-charged ions formation. Really, in this case resonance maximum in Ba^{2+} ions yield could be conditioned by two reasons: first, by increase of singly-charged ions concentration (step-wise mechanism) or by realization of resonce process in atomic spectrum (two-electron mechanism).

Under investigation of functions $lgN^{+}(lgF)$ and $lgN^{2+}(lgF)$ at different frequencies Ba^{2+} ions are observed in two different regions: first region where saturation of Ba atoms ionization is absent ($W\tau<1$) and second region where saturation of Ba atoms ionization ($W\tau\simeq1$) is realized. Note that in frequency region 18780-18960 cm^{-1} where the realization of step-wise mechanism of Ba^{2+} ions formation is unambigiously proved Ba^{2+} ions for the similar investigations were observed only in the region of Ba atoms ionization saturation [2]. In the first region we observed slopes $K_1^{2+}=7-9$ (dependent on frequency of laser radiation) and in the second region - $K_2^{2+}\simeq2.6$ (independent on frequency of laser radiation).

Observation of Ba^{2+} ions under investigation of functions $lgN^{+}(lgF)$ and $lgN^{2+}(lgF)$ in the region of absence of saturation of Ba atoms ionization and analisis of observed order of non-linearity as in the region of saturation as well in the region of absence of saturation of Ba atoms ionization unambigiously proves the realization of two-electron mechanism (direct double ionization) of Ba^{2+} ions formation.

Under intensity $F=2.1\cdot10^{29}$ $cm^{-2}s^{-1}$ which correspond to saturation of atom ionization for the fist time the magnitude of probability of two-electron mechanism realization was obtained: $W=10^{5.8}$ s^{-1}. Note that probability of Ba atoms ionization under this intensity was $W=10^{7.5}$ s^{-1}.

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FORMATION OF Ca^{2+} IONS AT MULTIPHOTON IONIZATION OF ATOMS BY RADIATION OF LINEAR AND CIRCULAR POLARIZATION IN 15000-18700 cm^{-1} SPECTRAL RANGE

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The investigations showed that for the majority of frequencies of resonant maxima in the yield of Ca^{2+} ions at both linear and circular polarization of laser radiation step-wise mechanism of doubly-charged ions formation is unambiguously prooved. At some frequencies resonant maxima in the yield of Ca^{2+} are identified in the model of step-wise mechanism only for linear polarization of radiation. For circular polarization this mechanism is not realized.

From the results of investigations of yield dependences of singly (N^+) and doubly (N^{2+}) charged ions on frequency (ω) under field strength $\mathcal{E}\simeq 1.5\cdot 10^7$ V/cm following conclusions could be made: a) relation between Ca^+ and Ca^{2+} yields is $N^+/N^{2+} = 3\cdot 10^1 - 10^3$; b) resonant maxima are observed in the yields of Ca^+ and Ca^{2+} ions; c) maxima in the yields of Ca^+ and Ca^{2+} ions in it's majority are observed on different frequencies; e) only two resonant maxima in the yields of Ca^+ and Ca^{2+} ions are observed at the same frequencies; f) the majority of resonant maxima in the yield Ca^{2+} are of large width (10-100 cm^{-1}); g) the majority of maxima in the yield of Ca^{2+} are observed at circular polarization. Note that for the first the process of doubly charged ions formation at multiphoton atom ionization was

observed by Buran and Zapesochny [1].

The performed analisis showed that the majority of maxima in Ca^{2+} yield at liner and circular polarization of radiation are unambiguously identified by resonant transitions in the spectrum of Ca^{+} ion at ionization of Ca^{+} ions from the ground 4s $^2S_{1/2}$ and excited 3d $^2D_{3/2,5/2}$ states. This fact proves the realization of step-wise mechanism of Ca^{2+} ions formation in these polarization of light. Performed investigations showed that only 2 from 11 maxima are not observed in the Ca^{2+} yield at circular polarization of radiation. The absence of these two maxima is well explained in the model of step-wise mechanism realization as the relevant transitions in Ca^{+} ion spectrum are forbiddened at circular polarization.

At the same time we observed some maxima in the yield of Ca^{2+} which are realized both at linear and circular polarization. These maxima are identified by resonant transitions in the Ca^{+} ion spectrum for linear polarization and couldn't be identified by the same transitions in Ca^{+} ion spectrum for circular polarization as these resonant transitions are forbidden for this polarization. This fact mean that at these frequencies step-wise mechanism is not realized at circular polarization. We can suppose the realization of two-electron mechanism (direct double ionization) at these frequencies. Thus the results of these investigations show that at linear polarization the most probable is the realization of step-wise mechanism and at circular polarization the two-electron mechanism is most probable.

Maxima in the yield of Ca^{2+} ions which coincide on frequency with maxima in the Ca^{+} yield couldn't be identified yet.

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EFFECTS OF RELATIVITY IN DIRAC-MODEL-ATOMS EXPOSED TO STRONG LASER-PULSES

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Rapidly growing interest in investigating non-linear processes in atomic physics has been triggered by the recent progress achieved in the development of high-intensity and short-wavelength laser sources. Relativistic effects are expected to have significant influence on the physics of laser–atom interaction in at least two different situations: On the one hand, conventional non-relativistic treatments lose their validity when the ponderomotive energy of the electrons acquired in an ultra-intense field is no longer small compared to the electron rest mass. This statement follows already from classical arguments. On the other hand, relativity affects the structure of the atom or ion, as it is described by Dirac theory in a quantum treatment. It is the purpose of this contribution to explore and discuss the significance of the influence of the relativistic fine structure and of the presence of the negative-energy continuum in the latter case.

While some effects due to fine structure and retardation can already be described in perturbative treatments of quantum electrodynamics, such as for instance two-photon transitions [1], the investigation of state populations, ionization and radiation emission due to the interaction with a short laser-pulse imposes a non-perturbative approach. For this reason the behaviour of a hydrogenic model-atom exposed to an intense laser pulse is now examined numerically. While

in ultra-intense pulses the magnetic field component induces a strong drift of the electron along the laser propagation direction [2], we can still restrict to a one-dimensional approach, regarding the laser intensities considered here. Present quantum relativistic treatments are until now only suitable for the regime of weakly relativistic intensities [3,4].

In our alternative method, the electron wave packet of the one-dimensional Dirac equation is time-propagated on a vector computer using a Fourier transform split-operator technique. The signature of relativistic effects on the photoelectron spectra, on the dynamics of ionization and on radiation emission are explored in detail. The results are compared to those of two different theories: A particle whose wavefunction obeys the relativistic Schrödinger equation, meaning the square root relativistic Hamiltonian in absence of a negative-energy continuum, and the ordinary non-relativistic Schrödinger prediction.

Though spin-dependent effects are absent in one dimension and the magnetic field component has no role, the Dirac particle still exhibits *Zitterbewegung* due to the presence of the negative-energy continuum. We address as well the importance of the Compton time and length scale governing the oscillations in the large and small components of the Dirac wave function.

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High-order Harmonic Generation in Dense Medium

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Ultimate possibilities of medium density increasing to enhance the efficiency of high-order harmonic generation by atoms in strong laser fields are considered based on a classical description of disturbing of ionized photoelectron motion in the continuum by neighbour ions.

Recent experiments show that quadratic growth of the efficiency of high-order harmonic generation with increasing of medium density is changed by a rapid fall at some critical density N_{cr}. This result was attributed [1] to ionization-induced defocusing of laser pump radiation. We have investigated another mechanism that works if photoelectron (after tunnel ionization) misses the parent ion (and does not recombine) due to disturbing of its motion in the continuum by neighbour ions.

Classical calculations of electron trajectories in the continuum were performed with simpleman approach and taking electron wavepacket spreading into account. Two regimes have been found to be realized depending on laser pump intensity I_p: single-collision electron scattering if $I_p < I_{cr}$, and multi-collision one if $I_p > I_{cr}$, where (for cut-off frequency Ω)

$$I_{cr}(\mathrm{PW/cm^2}) \approx 0.4\,(U_i / U_H)^{0.2}\, z^{0.8}\, \lambda^{-2.4} \quad ,$$

U_i and U_H are ionization potentials for medium atoms and H atom, z is a mean value of ion charge and λ is the laser wavelength (μm). The I_p-dependence of critical density N_{cr} (at which photoelectron entirely misses the parent ion) is essentially different for these regimes (Fig. 1): $N_{cr} \sim I_p^{-3/2}$ for single-collision regime and $N_{cr} \sim I_p^{3/8}$ for multi-collision one. The minimal value $N_{cr\,min} \sim \lambda^{-12/5}$ strongly depends on laser wavelength, e.g., for *Ne* atoms and z = 1: $N_{cr\,min} \approx 3 \cdot 10^{19}$ cm^{-3} for λ = 1 μm and $N_{cr\,min} \approx 10^{17}$ cm^{-3} for λ = 10 μm (these figures decrease with the increase of degree of atom ionization).

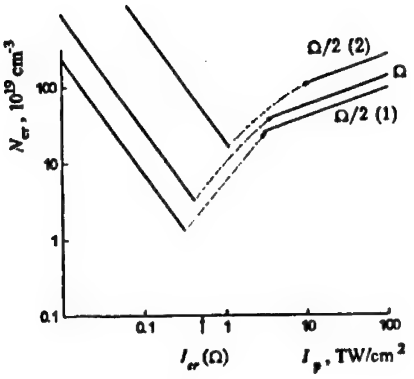

Fig. 1

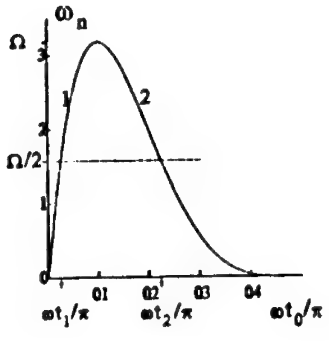

Fig. 2

Also, N_{cr} depends essentially on the phase of ionization ωt_0 (ω is a laser frequency). At first (with the density growth), the contribution of first branch of ionization (Fig. 2: $0 < \omega t_0 < \pi/10$) is eliminated (starting with the lower harmonic frequencies ω_n), then cut-off region is suppressed and, finally, the suppression of second branch contribution, that is a plateau (starting with the higher harmonic frequencies) occurs. Consequently, at high medium density the features of high-order harmonic generation are determined by the second branch of phases of tunnel ionization. Under such condition, the higher harmonics should be suppressed stronger with the increase of medium density (at laser intensity I_p = *constant*) and the decrease of harmonic suppression (for fixed harmonic number n) should occur with the laser intensity increase, that is in accordance with the experimental measurements [1].

Thus, with the medium density growth the fundamental restrictions to the increase of the efficiency of high-order harmonic generation could be imposed by the interaction of photoelectrons with the surrounding ions.

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Redistribution of electron energies at the interface between laser radiation filled space and vacuum

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Abstract

Using a simple one-dimensional model, we show that at the interface between a half-space filled by laser radiation and vacuum a considerable redistribution of the energies of electrons, either scattered or ionized in the laser field, takes place. This indicates that electron spectra evaluated by using electromagnetic plane wave fields for the description of a laser pulse, cannot reliably be compared with those data observed experimentally.

It is the purpose of the present note, to show by means of a simple, one-dimensional model calculation that there is a considerable energy redistribution of the electrons which get either scattered by an atom inside the laser beam and are emerging from it, or are created by ionization inside the beam and get off at the boundary of the beam. In order to simplify matters, we only consider the case in which the electrons pass the boundary of the laser beam along the direction of the laser polarization which is taken to point perpendicular to the interface between radiation filled space and vacuum, since usually the ionization probability is largest for electrons emitted parallel to the laser polarization, except for very high laser powers in the plateau region of the electron energy spectrum. Thus, assuming that the electrons escape the laser field perpendicular to the laser polarisation is of less interest. For simplicity, the above interface is approximated by a plane of infinite extent which is tangential to the laser beam and we also replace this interface by a sharp step such that the problem becomes largely tractable by analytic means. We are well aware that this assumption is not a quite realistic approximation. Moreover, we treat the laser field in the dipole approximation which is permissible for laser powers considerably less than the critical intensity of some $10^{18} W cm^{-2}$ and not too short laser pulses such that the space-dependence of the radiation field in the direction of propagation can be neglected and the assumption of adiabatic switching on and off of the laser field is justified. We are also aware that a radiation field having a sharp interface with vacuum, does in fact not fulfill Maxwell's equations. The present investigation is done in view of the recent experiments by Moore et al. [1] and Meyerhofer et al. [2] which authors were able to experimentally demonstrate the existence of the mass and momentum shift of an electron in a powerful laser beam, mentioned at the beginning.

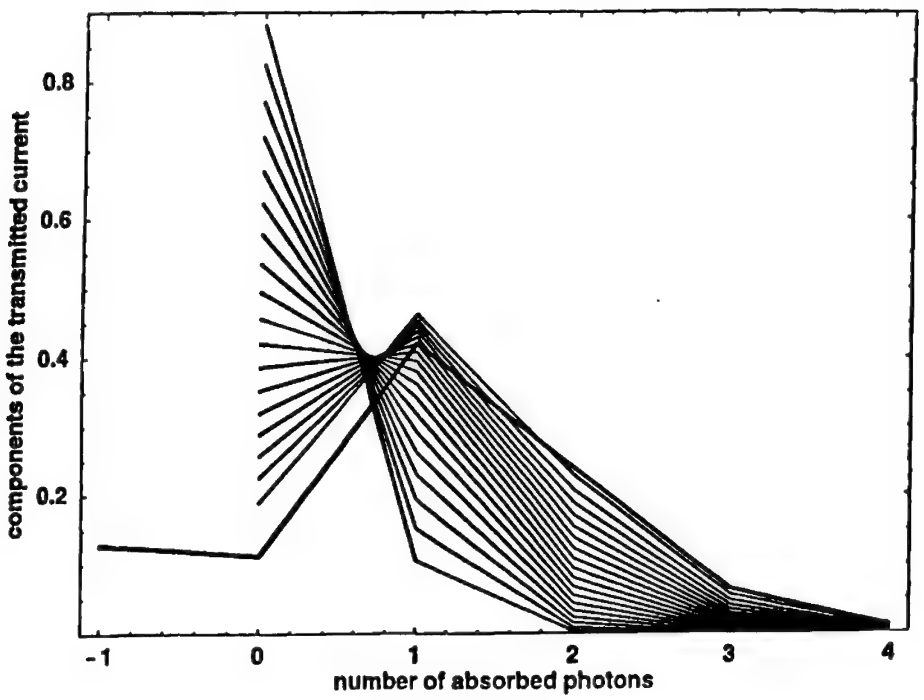

Figure Captions:

- **Figure 1**: If the initial electron kinetic energy in the laser field is chosen $E_{kin}' = 0.28eV$, the transmitted current components, $j_t(n)$, are shown as a function of the number of absorbed photons n. With increasing intensity I of the laser field, $j_t(0)$ is decreasing and, at the same time, $j_t(1)$ gradually increasing, while at an intensity of $10^{13}Wcm^{-2}$ the channel with $n = -1$ gets opened .

accuracy for fast-varying functions, because the function derivative is not constant over element. Though the number of nodes on one element increases when using cubic approximation, the total size of the problem can be eliminated due to the growing accuracy. Calculations performed for the test problem showed that cubic elements are more preferable than linear or quadratic.

Application of finite element method over spatial coordinates for free space quantum motion equation results in ordinary differential matrix equation in time. We use half-implicit differential scheme for this matrix equation. Using the Lagrange spatial grid for two-dimensional region allows to apply a split matrix method in order to replace one two-dimensional equation by two coupled one-dimention equations with sufficient accuracy [4].

Thus we developed an effective procedure for numerical modelling of two-dimensional non-stationary Schroedinger equation. Our method allows to model the desired processes on the spatial grid with 800x800 nodes, covering region more than 150x150 A, on the PC with Pentium 120, 16Mb RAM. Application of non-uniform grid makes it possible to describe most precisely regions, where potential function is quickly varying, and to create buffer regions near boundaries, where the behavior of the wave function can be neglected.

Determination of eigenfunctions of stationary Schroedinger equation is necessary to choose initial condition for non-stationary one and to interpretate the results of calculations. The application of the same cubic elements to the stationary equation results in the matrix problem on eigenvalues. This problem is solved by the method of iterations in subspace [5]. In most of the problems we are not interested in all spectrum of matrix eigenvalues, but only in eigenvalues which correspond to bound states. The method employed allows to determine effectively the several lowest eigenvalues and eigenfunctions.

Different physical processes (photoionization of 3D Rydberg hydrogen atom and two-electron 1D negative hydrogen ion, molecular hydrogen ion H_2^+ behavior in a strong laser field) are analysed on the base of these numerical codes. The results of our simulations are compared with different analytical theories for strong field atom and molecule ionization. As a result of this comparative analysis the theory of interference stabilization of Rydberg atoms [6] is proved, laser pulse parameters for the validity of different molecule photodissociation models are found [5], the validity of the nonstationary Hartree and Hartree-Fock approach for multielectron atoms in a strong laser field is studied.

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ADVANTAGES OF DIRECT NUMERICAL SOLUTION OF NON-STATIONARY SCHROEDINGER EQUATION IN THE INVESTIGATION OF QUANTUM SYSTEM DYNAMICS IN A STRONG LASER FIELD

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Effective numerical codes for the solution of the stationary and non-stationary Schroedinger equation are discussed. These codes allow to perform simulations of the strong electromagnetic field dynamics of 3D single electron systems or two-particle 1D model systems. The dynamics of ionization in short laser pulse for a number of quantum systems such as 3D Rydberg hydrogen atom, negative hydrogen ion H^- and molecular hydrogen ion H_2^+ is studied on the base of these codes.

Recently the method of direct numerical integration of the non-stationary Schroedinger equation has become one of the most effective method of investigation of the quantum system dynamics in intense laser fields [1]. Such "ab initio" simulations can be considered as numerical experiments and allow to study the evolution of quantum system in an intense laser pulse of femtosecond duration for conditions when validity of different known analytical approaches is doubtful.

Different processes (ionization of atoms and negative ions, ionization and dissociation of molecules, high order harmonic generation, laser induced bremsstrahlung, etc.) were studied by this method. The comparison of results of numerical modelling with the data obtained from different analytical theories provides the possibility to establish the range of their availability.

Usually single electron one-dimensional 1D models are used to study the quantum system behavior in a strong laser field [2]. But effective numerical codes for solution of stationary and non-stationary Schroedinger equation [3,4] make it possible to perform numerical simulations on two-dimensional spatial grid even on personal computers.

For numerical simulation of 2D non-stationary Schroedinger equation we use the following procudure: the first stage is splitting of the equation over physical factors. This means replacing general Schroedinger equation on the sufficiently small time step by two equations, describing distortion of wave function phase due to the action of laser field and existance of potential function of electron-nuclear or electron-electron interaction and free quantum particle motion.

The first equation is an ordinary differential equation in time for every spatial point and does not need any special method of solution.

Numerical modelling of the second equation, which is an partitial differential equation, is based on finite element method over spatial coordinates with cubic approximation of the wave function on the element. Such high-order approximation provides sufficient

MAGNETIC FIELDS OF LASER PLASMA FORMED AT HIGH-POWER RADIATION OF A TARGET BY A HF-LASER

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This report describes an experimental and numerical investigations of toroidal component of magnetic fields associated with a laser plasma formed at high-power radiation on a target (spot of irradiation $\approx 1cm^2$) by chemical HF-laser (λ=2,7-3,5 μm). The target from carbonaceous plastic material was located in a vacuum chamber (air pressure was about $3 \cdot 10^{-4}$ Pa). The output of the laser system ranged from about 100 J to about 2000 J in a 1-4 μs pulse, or about 25-2000 MW. The magnetic fields were detected by means of a inductive magnetic probe.

The detail analysis of this phenomena is investigated numerically for wide range of radiation and hydrodynamic parameters. The mathematical model includes a system of hydrodynamics equations, equation for a magnetic field in a plasma in linear approximation (describe the convection, diffusion and generation of the magnetic fields) and wave equation for consideration of the magnetic fields outside of the laser plasma flame. The numerical results of calculations are obtained as for dielectric target, as for target which conduct current . For both types of targets and in the space from both side from a target the directional diagram for magnetic fields are considered. The current-density distributions which produced the magnetic field as in a plasma as in the conductive target are presented. The experimental results for a magnetic fields are compared with numerical calculations.

THE COHERENT EFFECTS IN THE PROCESS OF HIGH HARMONIC GENERATION

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The analytical quantum approach is applied for the description of the atomic density dependence of HHG intensity (the effect of saturation). The phase matching effect is taken into account and the qualitative agreement between the theory and expetriment is demonstrated.

Resently in the experimental work of Lund-Saclay group [1] was investigaited the dependence of high harmonic generation (HHG) intensity on the atomic beam density. In the case of moderate densities (4 – 14 mbar) the intensity of HHG was established has the quadratic dependence with the atomic density. But this dependence saturates and after a threshold density does not increase. The threshold density depends on the harmonic number and the power of the pump wave.

In the paper presented the analytical quantum approach [2] is applied to describe qualitatively the effects observed in [1]. The multiphoton exitation of atom by the pump wave following by one quantum recombination to the ground state is considered. Thus the HHG is connected with the above-threshold ionization (ATI) process. The phase matching of emission amplitudes is taken into account. The quadratic dependence of HHG intensity with the atomic density is shown to be observed when the phase matching coherence length is larger than the diameter of atomic jet. The HHG intensity is going to be constant when the coherence length becoms smaller than this diameter.

To take into account the space dependence of focused laser light the simple model is proposed. By the use of this model the dependence of threshold density with the high harmonic number and the laser power is estimated. The comparison with experiment is presented.

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